UNIVERSITY OF ALBERTA

SPECIAL PURPOSE SIMULATION FOR TUNNEL CONSTRUCTION OPERATIONS

BY

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©

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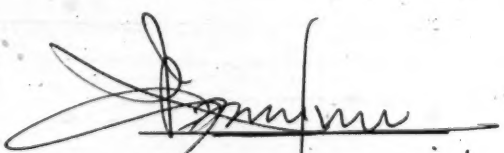

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled **"Special Purpose Simulation for Tunnel Construction Operations"** submitted by **Janaka Yasantha Ruwanpura Arachchige** in partial fulfillment of the requirements for the degree of **Doctor of Philosophy** in Construction Engineering and Management.

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This thesis is dedicated to my wife Senani for her love, affection and encouragement to successfully complete the graduate studies,

and

to my mother and late father for their encouragement and continued support throughout my entire education.

ABSTRACT

Computer simulation is a powerful tool for decision-making. It provides an appealing approach for analyzing and improving repetitive processes such as tunneling. Construction simulation also provides a great assistance to decision makers in analyzing various construction operations and alternatives and thereby experiment with different construction technologies, and estimate the possible consequences and impacts on scheduling and costs.

This thesis presents the design, development and successful implementation of a special purpose simulation (SPS) tool for utility tunnel construction operations including a new modeling technique to predict the soil types in the tunnel path, a major critical factor of tunnel construction productivity. The prediction of soil types during tunneling has been modeled using analytical methods. The thesis is comprised of two areas of research in addition to an SPS tool for tunnel construction operations that improves the overall process of tunnel construction operations.

The first part is the prediction of soil types and the combinations of soils from the surficial soil layer to the bottommost soil layer along the tunnel path, which provides the background information for the second part of the research. The second part is the prediction of soil transitions along the tunnel path using transitional probabilities that was implemented within the SPS template in tunneling. The prediction of soil types allows construction engineers to analyze the uncertainties in predicting soil types for tunneling in addition to the typical geotechnical explorations. The soil transition algorithms within the developed SPS template provide an accurate prediction of tunnel advance rates and productivity for tunnel construction operations.

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Chapter 1: Introduction

1.1 Introduction

Real world systems are so complex that some of these systems are virtually impossible to model and solve mathematically (Banks and Carson II 1984). In these instances, numerical and computer-based simulation can be used to imitate the behaviour of the system over time. A model is defined as a representation of a system for the purpose of studying the system. Although Mihram and Mihram (1974) and many other simulationists stated that it is not necessary to consider all the details of a system because thereby a model is a substitute and a simplification of a system, the model should be sufficiently detailed to permit valid conclusions to be drawn for the real system. The simulation model building process involves many steps. Problem formulation, setting up of objectives, model design and building, data collection, programming and validation, and implementation are the major steps. The art of modeling is enhanced by an ability to abstract the essential features of a problem, to select and modify basic assumptions that characterize the system, and enrich and elaborate the model until a useful approximation results. However, the model complexity need not exceed that required to accomplish the purpose for which the model is intended (Banks and Carson II 1984).

Computer simulation can be classified as either deterministic or stochastic depending on its uncertainty content (Wilson 1984). Since construction operations are subject to a wide variety of fluctuations, changes, interruptions, and uncertainties, most simulation applications use probabilistic simulation methods in simulating construction

operations. The input modeling, model design, and output modeling are critical issues in simulation modeling for any given situation. AbouRizk (1990) conducted in-depth research on modeling input data for the simulation of construction operations. There are many problems faced by the model designers and users when creating simulation models. When a real system is converted into a simulation model, several logical assumptions are applied. Sometimes these assumptions do not represent the correct nature of the real system. Uncertainty and unpredictable events in a real system are usually modeled using statistical distributions to reflect the actual occurrence of those events. A lack of historical data and its applicability to a statistical distribution may fail to successfully model such random events. Because of the high uncertainty involved in construction operations and the unavailability of historical quantitative data, various researchers have hypothesized the determination of activity durations for most construction operations. AbouRizk et al. (1994) divided certain input parameters for "certainty portions" and "uncertainty portions" based on the uncertainty content of the input parameters: deterministic analysis to estimate the certainty potion and probability and conceptual analysis to estimate the uncertainty portion.

Construction simulation can be of great assistance to decision makers in analyzing various construction operations and alternatives. Simulation of construction operations allows analysts and construction industry personnel to experiment with different construction technologies, and estimate their possible consequences and impact on scheduling and costs. Although simulation has been considered a very powerful tool for construction, its application to real life construction projects has been minimal (Ruwanpura et al. 2001a). The use of computer simulation for planning construction

projects has been limited to academia and a few large contractors who can afford to employ dedicated simulation professionals (Hajjar 1999).

This research produces a special purpose simulation application for utility tunnel construction operations and a modeling technique to predict soil types during tunneling for special purpose simulation. The uncertainty factors of the tunnel construction work have been identified through an application of project planning for tunnel construction operations. A critical factor of tunnel construction, the prediction of soil type during tunneling, has been modeled using transitional probabilities.

1.2 Research Objectives

The overall objective of this research is to develop a construction simulation tool for tunnel construction operations, and to develop a methodology to model a major uncertainty factor in tunnel construction using transitional probabilities, and implement the modeling concepts for simulation purposes to predict the tunnel advance rates and construction productivity. To achieve these objectives, the following sub-objectives and steps were identified.

1. Develop a special purpose simulation template for utility tunnel construction.
2. Apply the special purpose simulation template to the pre-project planning of tunnel construction projects and identify the critical factors that affect tunnel productivity.
3. Develop a methodology to define and characterize the main uncertainty factor in tunneling - the soil types - and define the profiles of major soil types to predict the possible distribution behaviour of the soil in a given area for tunneling.

4. Develop a modeling concept to predict the transition of soils during tunneling and implement it within the special purpose tunnel simulation template to determine the tunnel productivity.
5. Test and validate the soil prediction methodology and the tunnel simulation template using actual tunnel construction projects.

1.3 Research Summary

The research was conducted in three phases to accomplish the stated objectives. During the first phase, a special purpose simulation tool for tunneling was developed. The actual tunnel construction processes at the City of Edmonton Asset Management and Public Works Department were studied before creating the special purpose simulation template. The tunnel template was tested and validated and then applied for pre-project planning of a tunnel construction project in Edmonton. The application identified the factors that affect tunnel construction productivity and the limitations of prediction accuracy. The modeling of major uncertainty factors was identified. Ruwanpura (1999) identified the prediction of soil type as a major critical factor to improve the tunnel simulation template's accuracy.

During the second phase, geological conditions in Edmonton were studied to define and characterize the main soil types in the area to predict the possible combination of soil types, and the distribution behaviour, and the profiles of the soil types using an analytical and mathematical model. The prediction of soil types and families, which provides the pattern of the transition of soil types through an analytical approach, and the

transition from one family of soil to another could provide background information for the development of the third phase of research.

During the third phase, modeling concepts were designed to predict the transition of soils during tunneling and transition points along the tunnel trajectory using Markov transitional probabilities. The modeling concepts were then implemented within the special purpose tunnel simulation for tunneling. The new tunnel template was tested and validated for the project planning phase of tunnel construction projects.

1.4 Thesis Organization

Chapter 2 provides a summary of the state-of-the-art in computer simulation, tunnel simulation applications, soil prediction methods, and Markov applications in construction and geological applications.

Chapter 3 discusses the design and development of the tunnel simulation templates. It includes the evolution of the tunnel simulation template, the tunnel processes used for modeling, the purpose of simulation for tunneling, and the modeling layouts of one-way tunneling and two-way tunneling templates.

The testing and application of the tunnel simulation template for three tunnel construction projects are explained in Chapter 4. The successful application for project planning for a tunnel project and an application for bidding analysis for another tunnel project are presented in this chapter along with a case study of a tunnel construction project that was adversely affected by the geological conditions.

Chapter 5 introduces the soil prediction methodology using Edmonton geology for tunnel construction projects. The characterization and prediction of soil types and families, and the transition from one family of soil to another are discussed.

Chapter 6 presents the details of the modeling concepts to predict the soil transitions. The modeling algorithms and examples of tunnels are presented to illustrate the modeling concepts.

Chapter 7 explains the embellishments made to the tunnel template to model the soil prediction modeling concepts. The examples described in Chapter 7 are modeled using the tunnel simulation template and the results are presented.

Chapter 8 presents a case study for validating the modeling concepts described in Chapter 6 and 7. The final discussion is presented in Chapter 9 describing the findings, conclusions, contributions, and recommendations for further research.

Chapter 2: Background

2.1 Introduction

This chapter presents a summary of the state-of-the-art in computer simulation, tunnel simulation applications, soil prediction methods, and Markov modeling in construction and geological applications. Section 2.2 presents the summary of computer simulation and simulation modeling engines. Section 2.3 briefs the tunnel simulation tools and applications developed and implemented in the industry. Section 2.4 provides a summary of the soil prediction methods available within the construction industry applications including the background information on Markov theory, its applications in construction, and geological applications.

2.2 Construction Simulation

2.2.1 Overview

Computer simulation is defined as the process of designing a mathematical-logical model of a real world system and experimenting with the model on a computer (Pristker 1986). Early simulation users were required to build a model by writing programming code, mainly in FORTRAN, and experimenting by directly manipulating the computer program. This was followed by the invention of simulation specific programming environments where users write simulation specific code or access a provided function library. "Modeling" is the term used to describe the process of specifying a given

simulation model. In the next phase of development, a host of systems were introduced that allowed for alternative model development. This meant that modelers no longer had to write code directly. Graphical modeling made it possible to define the simulation model by creating, manipulating and linking a number of available basic building blocks. This meant that users no longer had to be proficient in programming. A detailed account of the history of simulation concepts and systems is detailed in Kreutzer (1986).

2.2.2 Simulation Modeling

There are many ways of modeling a given problem and these generally fall into two categories: continuous and discrete-event. Continuous or time-dependant algorithms are often represented with a system of equations or mathematical models and then solved for steady state performance using differentiation, integration, or approximation. In discrete event simulation utilizes "next event processing" of activities based on logical relationships between process components and availability of resources (AbouRizk 1998).

Users can typically change the behavior of a simulation model after it is constructed. This is the concept of the reusability where the model can be used for a multitude of scenarios. The degree to which users can change the pre-defined simulation behavior is dependent on the development strategy utilized. Simulation systems can generally be classified according to this feature as follows (Ulgen et. al. 1991):

a) Fully documented simulation models,

b) Parameterized simulation models,

c) Special purpose simulation program generators, and

d) General purpose simulation program generators.

With fully documented simulation models, users are required to modify the simulation models by manipulating them at the same level used to originally develop them. This assumes end users are knowledgeable with the way the simulation system works. Parameterized simulation models allow for model re-use by exposing a set of parameters that users can modify each time the model is simulated. The values of the parameters can be used to modify routing strategies, resource values and entity attributes. With special purpose program generators (SPSPG), users are able to create models by selecting from a list of available domain-specific constructs and defining their parameter values as well as their relation to other elements. Examples of such systems include WITNESS and SIMFACTORY (Mathewson 1989), Ap2Earth (Hajjar and AbouRizk 1996), CRUISER (Hajjar and AbouRizk 1998) and CSD (Hajjar et al. 1998). The advantages of special purpose simulation program generators are outlined in AbouRizk and Hajjar (1998). General-purpose simulation program generators (GPSPG) are like SPSPG; only expert users can add new modeling constructs to the system.

Halpin (1977) popularized the use of simulation in construction research with his invention of a system called CYCLONE (CYCLic Operation NEtwork). CYCLONE allowed the user to build models using a set of abstract but simple constructs. The system became the basis for a wide range of construction simulation research efforts with the objective of enhancing the basic system functionality and most construction

simulation work was motivated by the success of CYCLONE (AbouRizk 1998). This Included INSIGHT (Paulson et al. 1978), UM-CYCLONE (Ioannou 1989a), and RESQUE (Chang and Carr 1987). STROBOSCOPE (Martinez and Ioannou 1994) was another development based on CYCONE which allowed for dynamic simulations based on the definition of entity and resource attributes using programming - like syntax. DISCO (Huang et al. 1994) developed to allowed the use of graphical-based modeling for CYCLONE models. Although CYCLONE and its derivatives introduced a wider academic audience to computer simulation, its use in the industry was very limited (Hajjar 1999).

Simphony is a simulation platform for building general and special purpose simulation tools, which was developed under the Natural Science and Engineering Research Council (NSERC)/ Alberta Construction Industry Research Chair Program in Construction Engineering and Management. It is a Microsoft Windows based computer system developed with the objective of providing a standard, consistent, and intelligent environment for both the development and utilization of special purpose simulation (SPS) tools (Hajjar and AbouRizk 1999). AbouRizk and Hajjar (1998) also defined SPS as *"a computer-based environment built to enable a practitioner who is knowledgeable in a given domain, but not necessarily in simulation, to model a project within that domain in a manner where symbolic representations, navigation schemes within the environment, creation of model specifications, and reporting are completed in a format native to the domain itself."*

Intended application domain, simulation theory, and object oriented programming are the three key ingredients for developing a special purpose simulation tool. The

successful design and implementation of a special purpose simulation tool depends on the flexibility of the modeling environment and on its user-friendliness. In this respect, Simphony fulfills the requirements: its object oriented application framework provides a structured approach to build any simulation template with ease, including graphical, hierarchical, modular, and integrated modeling techniques. A detailed introduction to Simphony can be found in Hajjar and AbouRizk (1999).

2.3 Tunnel Simulation Tools and Applications

In general, the term "tunneling" can be used to describe a wide range of underground excavation operations. Tunnels can be used to serve a variety of functions, including subways, utility corridors, and sewer lines. Tunnel construction projects are particularly suitable for simulation due to the many repetitive construction cycles that occur during construction. Simulating the process of tunnel advancement can guide the engineers, planners, and constructors to plan and control the project more efficiently. It is generally accepted that tunneling projects are typically high-risk. Successful project planning can save both cost and time, resulting in a productive tunnel construction project (Ruwanpura et al. 2001a)

Touran and Asai (1988) predicted the tunnel advance rate in the construction of a several-mile-long, small-diameter tunnel in soft rock using CYCLONE. Tanaka (1993) presented a tunnel simulation using CYCLONE for shielded tunnel boring machines. AbouRizk et al. (1997) applied tunnel simulation using Visual SLAM to analyze the productivity of construction activities for a tunnel constructed under a river to validate a

productivity claim. Olufa et al. (unpublished) presented a library-based simulation modeling development with an implementation in shielded tunnel construction projects. They used an object-oriented simulation programming language called MODSIM to simulate the tunneling projects. Salazar (1987) presented a simulation model based on the event scheduling approach to generate probabilistic descriptions of the advance rate of tunnel excavation and the corresponding demand for resources. It used linked lists to dynamically schedule construction activities as the excavation takes place through difficult ground conditions and provided two case studies comparing two tunneling methods to illustrate the model. These tunnel simulation models have catered to particular situations and cannot be used for other types of tunnel construction projects.

Ruwanpura et al. (2000b and 2000c) discussed the independent studies conducted by two graduate students Hajjar (1997) and Ruwanpura (1998) of the University of Alberta as part of their course work, to model TBM-based tunnel construction using Visual SLAM (Pritskar 1994). However, both models were not flexible enough to model for any given tunnel construction project using a TBM, and were not validated using a construction project. In both cases, they concluded that simulation could be a very useful tool for project planning.

2.4 Soil Prediction Methods

2.4.1 Introduction to Markov Theory

The Markov chain, named after the Russian probability theorist A. A. Markov, is a particular class of probabilistic models that are often applicable to decision making in

business and industry. A Markov chain is a special case of the more general probabilistic models known as stochastic processes, in which the current state of the system may depend on all previous states. A Markov process is a stochastic process distinguishable by the fact that the current state of the system depends only on the previous state of the system (Lee et al. 1990). Since the construction operations are susceptible to fluctuations of various factors and variables, which enforce the changes in the system, the use of Markov chains is very appropriate for simulation of events. The Markov chain has the ability to model the changes that happen in a system over time. Stochastic models may be a more realistic approach than any deterministic models because of the ability to take into account uncertain factors. In simple first-order Markov chains, the probability of the future condition state does not depend on the past, but only on the present condition state. A Markov chain process predicts future condition states of elements, based on the current condition state, and the probabilities of transitioning from one condition to another (Jiang and Sinha 1992). Hence, Markovian models are helpful in representing various situations in which a system moves from state to state based on a set of transitional probabilities (Halpin and Riggs 1992). A matrix easily represents the transition probabilities, and Markov chains can be homogeneous, or non-homogeneous, and discrete-time or continuous time. If the transition probability matrix is assumed to be constant for each state, it is homogeneous for one particular application.

2.4.2 Previous Literature on Application of Markov Chains

Markov properties have been recognized in many geological phenomena, including stratigrahic sequence of lithologic units, sedimentary processes, stream drainage

networks, successions of mineral occurrences and many other cases. As a result, the geological literature on Markov Chains has increased rapidly. Almost all of the studies aimed to predict various geological requirements vertically using Markov Chains. No relevant study was found on predicting the soil types or stratigraphic information horizontally using Markov Chains or any other analytical technique except Ashley et al. (1981) and Ioannou (1988b). The application of Markov Chains in construction and geological areas are explored under two headings:

a) Modeling of uncertainty of various factors for construction applications using Markov Chains
b) Markov chains in Geology.

2.4.3 Modeling of Uncertainty for Construction Applications

Weather is one of the main uncertainty factors modeled by various researchers. They have conducted studies to predict weather, construction productivity, and durations of activities. Some research work to model weather conditions used a combination of many concepts such as simulation, Markov chains, fuzzy sets, and statistical probability theories. Significant work in area has been done by Benjamin and Greenwald (1973), Carr (1979) Woolery and Crandall (1983), Ayub and Halder (1984), Ahuja and Nandakumar (1985), Smith and Hancher (1989), and Wales (1994). Application of Markov chains to model uncertainty factors in construction has been minimal and used first order two-state Markov chains.

Ashely et al. (1981) proposed a probabilistic geological prediction using a discrete-state, continuous-parameter Markov model. They used information that was

available during construction to update the probabilistic descriptions of the geologic conditions ahead of the tunnel face. The model's viability was demonstrated through a case study analysis of a power station tunnel. The results of the prediction and updating were in the form of probabilistic ground class profiles which were needed to select the economically optimal and technically appropriate tunnel design and construction procedure. The same case study was used by Ioannou (1988b) to present a general model for the probability prediction of tunnel geology as a basis for developing more effective tunnel design and construction decision systems. The geologic conditions along the tunnel alignment are modeled by a set of geologic parameters such as rock type, joint density, degree of weathering, and water availability, each following a continuous space, discrete-state Markov process. This study did not show the interaction of the soils and mixed phases of soils in the boreholes in the tunnel alignment. The resulting geologic parameter profiles generated from the study were aggregated into a single probabilistic ground class profile to determine the optimal tunnel design and construction strategies.

Smith and Hancher (1989) conducted studies to produce a model that would provide a method that combined the information derived from a Markov-process model of rainfall and qualitative information regarding the impact of the rainfall events evaluated with fuzzy sets. The first-order Markov chain was used to model a two-state Markov process (dry and rain). Although there is no direct relationship between the results of the Markov process and the fuzzy sets in that model, the delay caused by rain has been modeled using the linguistic terms interpreted using fuzzy sets. The authors concluded that the construction of relationships between the factors that affect productivity requires more attention.

Wales (1994) modeled the effect of weather using first order two-state Markov chains and quantified its impact on productivity and adjusted the durations to reflect the project conditions. He used a combined discrete-event continuous simulation modeling concepts. His studies emphasized that it is possible to accurately include uncertainty factors like weather in project simulation studies.

Ariaratnam (1994) proposed a probabilistic approach to formulating a failure prediction model for bridge maintenance, rehabilitation, and restoration that incorporates a Markovian process that provides information on the probability of moving from one condition state to another, given the present state. This model generated curves depicting deterioration patterns for the three main components of the bridge: wearing surface, superstructure, and substructure.

Adams and Sianipar (1995) used Markov processes to model the network level bridge management system. The authors felt that the stochastic models may be a more realistic approach to bridge deterioration because of their ability to take into account uncertain factors. They mentioned that the transition probabilities could be obtained from expert elicitation or based on historical data. The holding time in each condition state and the probability of jumping from one condition state to another were the two parameters considered in the Markov process.

Touran (1997) used Markov processes to develop an analytical model to two states of operation (work or non-work) of a tunnel-boring machine in a tunnel project in Boston. The results of the Markov chains were used to propose a general probabilistic model to develop the cumulative density function of the total tunnel length that can be tunneled in a given time framework. Simulation models were developed to verify the

results of the analytical model and also to simulate the time necessary to tunnel the remaining length of the tunnel.

2.4.4 Markov Chains in Geology

Almost all the applications in geology using Markov chains are targeted to predict the soil profiles vertically. No significant work was found where the prediction of soil profiles horizontally was the focus. Krumbein and Dacey (1969) structured the geological data as first-order, discrete-state discrete time Markov Chains in two main ways. In one, observations are spaced equally in time or space to yield transition probability matrices with nonzero elements in the main diagonal; in the other, only state transitions are recorded, to yield matrices with diagonal elements exactly equal to zero. They evaluated the mathematical differences in these two approaches using stratigraphic data. They concluded that simulations from chains with diagonal elements greater than zero always yield geometric distributions of lithologic unit thickness, and their use was recommended only if the input data have the same distribution.

Dacey and Krumbein (1970) further proved that there was a close agreement between the observed and calculated thicknesses of lithologic units after testing a Markov model against stratigraphic data obtained from micro logs.

Schwarzacher (1969) concluded that the method of Markov chains and discrete stochastic chains, in general, is a cumbersome tool when applied to stratigraphic analysis and recommended the use of Markov chains for description of geological cycles.

Eithier (1975) stated that the treatment of sedimentary sequences by Markov-chain analysis is intuitively appealing because stochastic modeling seemed well-suited to

the type of geological data. Application of Markov-chain techniques to the Banff formation, a carbonate-shale sequence that shows repetitive but not obviously cyclic pattern. The research demonstrates important limitations in using the technique as a practical tool in the interprétation of this type of sedimentary sequences. The author pointed out that the sequence should be long or thin-bedded to allow a minimal number of transitions; alternatively lithologic entities may be combined, but geologic interpretation may not be well served and information is inevitably lost.

Le Roux (1992) provided a modified method comparing the two methods discussed earlier. The modified method combined the two basic methods and introduced a proportional difference matrix to remedy the effect of deficient cells in the transition-count matrix.

Xu and Maccarthy (1998) presented a computer software package for statistical analysis of vertical facies sequences (SAVFS). SAVFS provides three analytical methods based on the combination of some generally used methods mentioned previously, which eliminates the difficulties and mistakes in hand calculations, particularly in the improved embedded Markov Chains methods of Powers and Easterling (1982) and Harper (1984), surpassing the procedures used by Gingerich (1969) and Selley (1970), which are time consuming.

2.4.5 Other Soil Prediction Methods for Construction Applications

Ioannou (1988a, 1988b, 1989b) presented an extensive study of predicting the uncertainty in underground construction promoting design and construction conservatism and how to make a significant impact on project costs. As part of this extensive study, Ioannou

(1988b) presented the contractor's view concerning the usefulness of constructing a pilot tunnel as part of the site investigation program and offers guidelines for evaluating its benefits. These benefits included furnishing information about the geology and its behaviour and facilitating design development and construction operations. Ioannou (1988a) presented research findings that provide a better understanding of how subsurface exploration and improved contractual risk sharing can decrease the cost of underground projects. The issues discussed in this paper were the methodology used by tunneling contractors to estimate geologic profiles given a set of geologic information, geologic classification methods used to associate the expected profile with acceptable construction alternatives, the spatial prediction of ground classes and their extents over different excavation and support methods, and then to estimate the tunnel advance rates based on Ioannou (1987), described in section 2.4.3.

Wu et al. (1996) presented a site characterization model that accounts for geologic information, and uses probability to draw inferences from data specifically on sand and gravel units in glacial sediments. The authors also emphasized the expert's opinions to revise the methods to produce the final conclusions as it incorporates the experience and judgment for site explorations strategies previously approved by Rehak et al. (1985), Halim et al. (1991), and Toll (1995). Length or width, thickness, and occurrence rate were the properties considered in determining the prediction of sands and gravel.

Geotechnical design requires the interpretation of ground conditions from site investigation information. This normally requires interpolating or extrapolating from observing at discrete points, such as boreholes (Toll et al. 1993). Vaptismas and Toll (1993) outlined an approach of a computer system that can assist in producing an

interpretation of the ground conditions at a site based on discrete observations at boreholes. The process identified a site-wide model of the ground conditions using marker beds; these are layers which 'stand out' from the general ground conditions and easily trace across a site. The continuity of the marker beds was examined at a number of levels, building up to describe the site-wide trends. In this study, the detailed ground conditions are examined at a borehole-to-borehole level by examining all layers in neighbouring boreholes, thereby assisting the engineers both in achieving an outline of the ground conditions and to indicate areas within a site where complex conditions exist. Toll (1995) followed this work and then developed a knowledge based (expert) system to help engineers with the processing of raw site investigation data to arrive at interpreted design parameters and a model of the ground conditions. Oliphant et al. (1996) produced a new methodology for interpreting ground conditions based on the boreholes using an ASSIST (Advisory System for SIte InveSTigation) comprising three sub-systems. Preliminary site investigation, data acquisition, and main site investigation are the components.

Chapter 3: Design and Development of a Special Purpose Simulation Template for Tunnel Construction Operations[1]

3.1 Introduction

Computer simulation is a powerful tool for decision-making. It provides an appealing approach for analyzing and improving repetitive processes such as tunneling. Notwithstanding this appeal to date, application of simulation to real life construction projects has been minimal. This chapter presents the design and development steps of the special purpose simulation (SPS) template for tunneling that was successfully implemented in the industry for project planning and decision making processes. The tunnel template described in this chapter is the first special purpose simulation template successfully implemented to the industry which was designed using the Simphony SPS engine. The tunnel template provides the following improvements to the state-of-the-art of construction simulation applications for construction operations.

1. Flexibility in the design of the modeling layout and the modeling elements (explained later in the chapter) allowing the end user to simulate several construction alternatives of tunneling by only changing either the values of input parameters or the layout of the modeling elements.

[1] This chapter mainly contains extracts from the paper "Special Purpose Simulation Templates for Tunnel Construction Operations" published in the Canadian Journal of Civil Engineering, CSCE, 28(2), 222-237.

2. Design of graphical user interfaces in the modeling elements to depict the construction options (or the meaning of the modeling element within the application) or the construction layout. This allows the experienced end user of tunneling who is not familiar in simulation to create a model with ease.
3. Adaptability of the hypothetical work conditions for modeling scenarios including the work shift suspension.
4. The first simulation tool in the industry that predicts the cost planning information that includes the basic costs, operational costs, and support costs, productivity, duration and resources utilization based on the simulation of the tunneling operations.
5. Ability to model several scenarios (or construction options) of the same construction operation without modifying the structure of the modeling elements or its programming code.
6. The flexible and logical application of continuous simulation concepts within the discrete-event simulation framework.

The template was developed collaboratively with City of Edmonton Asset Management and Public Works Department under NSERC/Alberta Construction Industry Research Program in Construction Engineering and Management. The objective of this simulation tool was to introduce the industry to a simulation based analysis for planning tunnel construction projects. The tunnel construction work performed by City of Edmonton was studied before creating the special purpose simulation template. City of Edmonton has completed approximately 500 kilometers of tunneling projects over the last five decades.

While City of Edmonton has fifty years of experience in tunneling, this is the first time they have employed simulation for planning and analysis purposes. This chapter is organized as follows: Section 3.2 provides the historical and general information about tunnel construction in City of Edmonton. Section 3.3 explains in detail the tunnel construction processes. The evolution of the tunnel simulation tools is described in Section 3.4. Section 3.5 discusses the purpose of simulation in tunnel construction projects. The SPS based tunnel simulation template are presented in Section 3.6 including the structure of the template, features of the template, and modeling parameters, processes, outputs and statistics. The challenges faced during design and development and the conclusions are presented in Section 3.7.

3.2 Tunnel Construction History at City of Edmonton

City of Edmonton started developing its tunneling expertise in the early part of the 1950's, beginning with hand tunneling. In 1965, a non-shielded tunneling boring machine (TBM) was designed and fabricated. After ten years, City of Edmonton purchased its first shielded TBM, and later purchased four more. The use of TBM boosted their ability to construct TBM tunnels, with excavation as large as 6.8 meters diameter tunnels. Open face TBM machines (Figure 3-1) have been used to construct tunnels of 1.93 to 5.50 meters in diameter.

City of Edmonton presently has four sizes of closed face shielded machines (Figure 3-2) with excavation diameters of 2.54, 3.20, 4.47, and 6.20 meters. Tunneling by manpower resources or hand tunneling is mainly suitable for shorter length tunnels.

Depending on the size of the tunnel, an excavation crew is deployed at the tunnel face in hand tunneling. They typically use jackhammers, drills, and shovels for excavation. Hand tunnels vary from 0.91 to 3.20 meters in diameter. Hand tunnels are typically excavated in different shapes, such as arches, ovals, and horseshoes (Ruwanpura et al. 2000a). Table 1 summaries briefly the tunneling processes involved in TBM tunneling and hand tunneling.

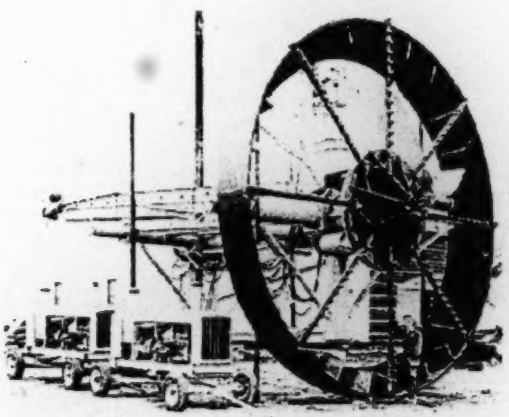


Figure 3-1: Open Face Tunnel Boring Machine

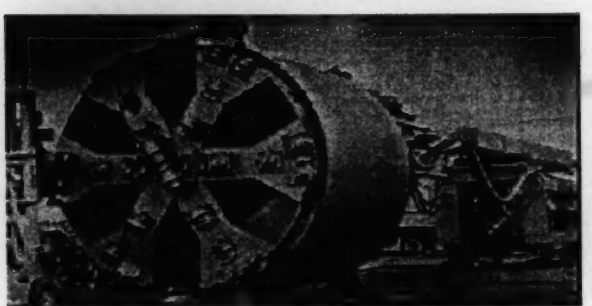


Figure 3-2: Close Face Tunnel Boring Machine

3.3 Tunneling Processes

Tunneling projects involve three main processes: excavation, dirt removal and tunnel support. The process of tunnel construction commences with the excavation and liner support of a vertical shaft to a depth corresponding to the invert level of the tunnel excavation. The other typical tunnel activities are:

1. excavation and support of the undercut area (an enlargement at the bottom of the shaft used for staging material handling and dirt removal operations),
2. excavation of the tunnel and tail tunnel,
3. disposal of dirt from the tunnel face,
4. hoisting the dirt to the ground level,
5. lining the tunnel,
6. extending the services and rail tracks, and
7. excavation and support of the removal shaft (if a TBM is used).

There are two types of tunnel boring machines: open-face and closed-face shielded machines as explained in Section 3.2. Open-face machines are generally used in competent soils with reasonable stability. In conditions of runny soils, such as silt or sand, a closed-face shielded machine is utilized. An important property of TBMs is their excavation rate, which is dependent on the soil conditions and the TBM horsepower. Another important property is the stroke length, which determines how often the TBM will need to be reset.

Table 3-1: Summary of Tunneling Methods Performed at City of Edmonton[2]

Process	Open Face TBM	Close Face TBM	Hand
Excavation	TBM bores until achieving the stroke length. The stroke length can be as same as the rib spacing of the preliminary liners.	TBM bores until achieving the stroke length. The stroke length is set for the length of the liner spacing (usually one meter).	Tunnel diameters less than 2.1 meters, boring is done until the rib spacing is achieved. For tunnel diameters of over 2.1 meters, the top section of the tunnel is bored and then the primary liner is placed before excavating the bottom section. Initially three top sections are excavated before excavating the first bottom section to ensure that two top sections are always ahead of one bottom section.
Dirt Removal (Tunnel Face to Shaft)	Trains (one or two) and muck cars.	Trains (one or two) and muck cars.	Typically using one train and a few muck cars (capacity less than the volume to be hauled for one rib spacing of excavation).
Hoisting of Dirt (Shaft to Ground)	A crane, a derrick hoist, a clamshell, or a gantry.	A crane, a derrick hoist, a clamshell, or a gantry.	Mostly a small crane or a clamshell.
Liner Support	Rib and Lagging (primary liner), and in-situ concrete (secondary liner). The secondary liner is placed when tunnel excavation is finished. The rib spacing can be 1.0, 1.22 or 1.5 meters.	Pre-cast concrete segments liners soon after stroke length (one meter) of tunnel is excavated OR Rib and Lagging (same as open face TBM)	Rib and Lagging (primary liner), and in-situ concrete (secondary liner). The secondary liner is placed when tunnel excavation is finished. The rib spacing can be 1.0, 1.22 or 1.5 meters.

[2] This Table was first published in "Special Purpose Simulation Templates for Tunneling" in proceedings of the Construction Congress VI, ASCE, Orlando, FL, pp. 97-106

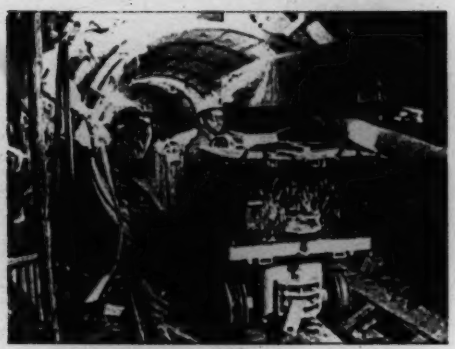


Figure 3-3: Train and Muck Cars – Dirt from Tunnel Face to Undercut

The dirt handling process involves the transportation and disposal of spoil from the tunnel face to the shaft, where it is lifted to the surface. Spoil can be hauled horizontally using trains (Figure 3-3) and/or belt conveyors. The selection criterion depends on the tunnel site conditions. Belt conveyers have the advantage of providing a continuous spoil removal system. However, they typically require excessive maintenance. Train haulage is energy-efficient, and compatible with most excavating and loading methods, and is adaptable to almost all sizes of tunnels. Trains can also be fitted with special cars capable of transporting laborers and support liners. Depending on the tunnel diameter, a single or double-track system can be used. In most cases, a track switching system is utilized at the undercut to allow multiple trains to share a single track. The working shaft is utilized to remove the spoil and to transport the construction materials and personnel. The dirt can be hoisted with a skip, a clamshell bucket, a crane, a gantry, or a derrick hoist. Clamshells are typically used in shallow tunnels. In medium depth tunnels (10 to 20 meters), gantries or cranes are more economical, and in deep tunnels (>30 meters), a cage or skip is used with a derrick hoist. Figure 3-4 shows the muck car with dirt being lifted by a crane.

Figure 3-4: Lifting a Muck Car with Dirt

The two major types of tunnel support systems consist of either (1) rib-and-lagging or (2) concrete segments. The rib-and-lagging method (Figure 3-5) has a record of high performance in a variety of ground conditions. During installation, lagging is wedged circumferentially between rib and soil. The rib-and-lagging support system acts as the primary lining system. A secondary layer made of cast-in-place concrete is placed when tunneling excavation is finished. Pre-cast concrete segment lining (Figure 3-6) is the alternative to rib-and-lagging. Pre-cast liners act as both the primary and final lining. Each segment is designed as a compact structural unit, and thus requires the least amount of handling during erection. The full ring typically consists of four identical segments. It is partially installed inside the shield of the TBM, and the ring is expanded tightly against the soil as it leaves the shield. Metal spacers are inserted in the gap created by the ring expansion to maintain its structural integrity. The gap is subsequently filled with concrete, and the joints are patched with cement mortar.

Figure 3-5: Rig and Lagging Method

Figure 3-6: Pre-Cast Concrete Segments

3.4 Evolution of Simulation Template for Tunnel Construction Operations

The evolution of Simphony (explained in Chapter 2), a simulation platform for building general and special purpose simulation tools, developed under the NSERC/Alberta Construction Industry Research Chair Program in Construction Engineering and Management was the main motive to create a tunnel simulation template. This development of this simulation tool was also a direct result of the collaboration between the City of Edmonton and NSERC/Alberta Construction Industry Research Chair Program in Construction Engineering and Management.

The template is based on the special purpose simulation concepts described in AbouRizk and Hajjar (1998). The end user is given the opportunity to create a simulation model for a given scenario using the modeling elements in the tunnel simulation template. The modeling behaviour for the preliminary version of the template was based on a previous development of a tunnel simulation models (Figure 3.7) completed by two graduate students (Ruwanpura et al. 2000c) at University of Alberta in 1997 and 1998.

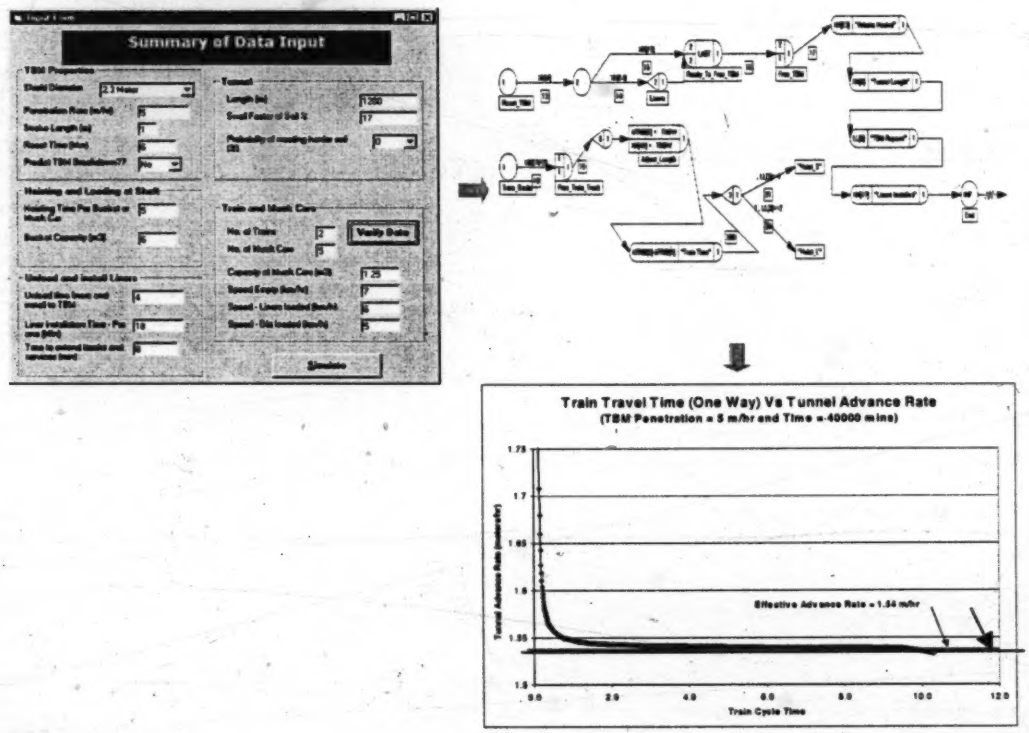

Summary of Data Input
Train Travel Time (One Way) Vs Tunnel Advance Rate
(TBM Penetration = 5 m/hr and Time = 40000 mins)
Effective Advance Rate = 1.54 m/hr
Train Cycle Time

Figure 3-7: Part of the Simulation model for tunneling using Visual SLAM, developed in 1998

3.5 Purpose of Simulation for Tunneling Projects

The progress of the overall tunneling project is dependent upon the progress of the individual activities explained previously. Any planning exercise that attempts to optimize the overall operation must examine the system as a whole. Improvement in one activity such as tunnel excavation must be balanced with improvements in related activities such as dirt transportation. The system is optimized when all activities are synchronized to minimize the waiting or idling time and the resources are 100% utilized. It is therefore important to evaluate improvement to an activity that impacts the waiting times and the utilization of resources leading to a minimum unit cost. The tunnel advance rate is perhaps the most important measure of efficiency for tunneling projects, as investigated by Touran and Asai (1988). This indicator is dependent on many factors, including:

(1) TBM excavation rate (boring rate)

(2) Soil conditions and swell factor

(3) Reset and liner installation durations

(4) Number of trains

(5) Optimal number of muck cars and their capacity

(6) Required train velocity

(7) Spoil removal productivity

One way to analyze a tunneling system is to examine the various cycles that occur. In general, two cycles exist: the tunnel face cycle and the material handling cycle at shaft. All activities at the tunnel face are repetitive. Figure 3-8 shows the schedule for the

repetitive activities at the tunnel face. No wait time is shown in the schedule for illustrative purposes: it is assumed that the muck cars are available to commence the next cycle. However, the entire schedule depends on the travel time of the train and the other repetitive operations at the shaft. In a two-train situation, the second train could arrive at any time. At optimum, the second train arrives at the tunnel face when the liner installation is completed. If the second train is late, the TBM waits until it arrives. Therefore, there are two waiting factors that determine the production and the tunnel advance rate: train-waiting time for the TBM, or TBM waiting time for the train.

The activities at the shaft also involve repetitive operations. Figure 3-8 shows the schedule for the activities that occur at the shaft. The processes at the shaft depend on the travel time of the train and the operations at tunnel face, plus the efficiency of the hoisting operations at shaft. It is also assumed that there is no waiting time for any of the resources in the schedule. The second train could arrive at any time. At optimum, the second train arrives at the shaft when the first train has finished loading the liners and unloading the dirt. If the second train is delayed, the crane waits for the train.

Ruwanpura et al. (2000c) documented the following main reasons for using simulation for tunnel construction operations.

(1) Project Planning: Simulation has the ability to model a hypothetical situation using a computer. Computer simulation enables the planners to plan the sequence of work activities, declare the method of operation, select the suitable resources for the given project, and analyze the production of the system before commencing actual construction.

(2) Identifying bottlenecks in tunnel operations: Some of the problems that may happen in a typical tunnel construction project could be detected using the results of the simulation model. Identification of these problems helps the planners and engineers to decide on corrective measures before actual construction commences.

(3) Examining productivity improvements and optimizing resource utilization: The typical outputs of a simulation model for tunneling are productivity, tunnel advance rate, and resource utilization. Using a simulation model, planners and engineers can observe productivity and resource utilization levels and conduct additional testing to improve the efficiency of the system using the available resources.

(4) Offering a quick comparison of alternative tunneling scenarios: This is the one of the main advantages of using simulation for any construction operation. Simulation allows planners to not only predict the actual results, but to compare the results using several scenarios. For example, the utility tunnel construction operations could be planned using different methods using different resources to achieve the same goal. Simulation offers a very quick comparison for alternate scenarios and allows the planners to make informed decisions before they embark on the project.

3.6 Simulation Template for Tunneling

The Tunneling template is a special purpose simulation tool for design and analysis of tunnel construction projects. There are two versions of TBM tunneling template: one for one-way tunneling using one TBM, and another for two way tunneling using two TBMs. Both versions of the template allow the user to experiment with a number of alternatives when planning a tunnel construction project. The tunnel template:

(1) Predicts the tunnel advance rate which depends on various deterministic and stochastic factors such as length of the tunnel, depth of the shaft, muck car capacity, train speed, dirt volume and removal method, soil conditions – swell factors, penetration rate, etc. All the deterministic and stochastic factors are described in Table 3-2.

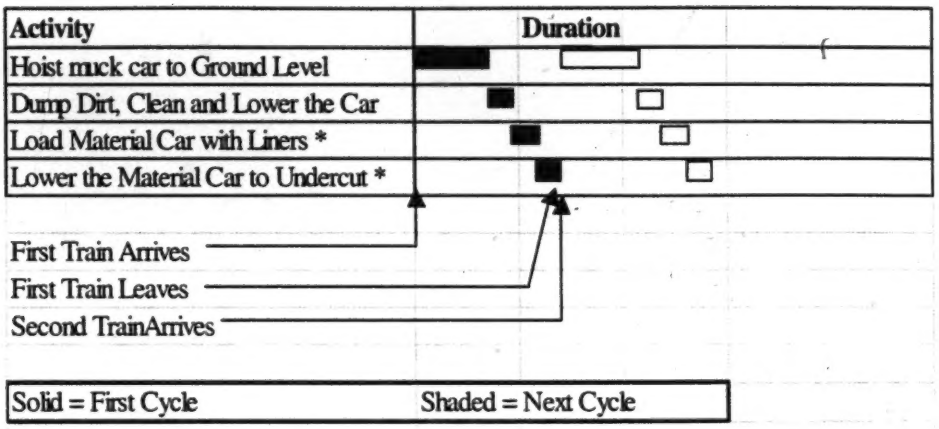
(2) Balances the construction cycles at tunnel face and shaft and optimizes the use of the TBM, crane, and trains.

(3) Predicts the productivity, cost, schedule, and resource utilization based on the simulation analysis.

3.6.1 Structure of the Tunnel Template

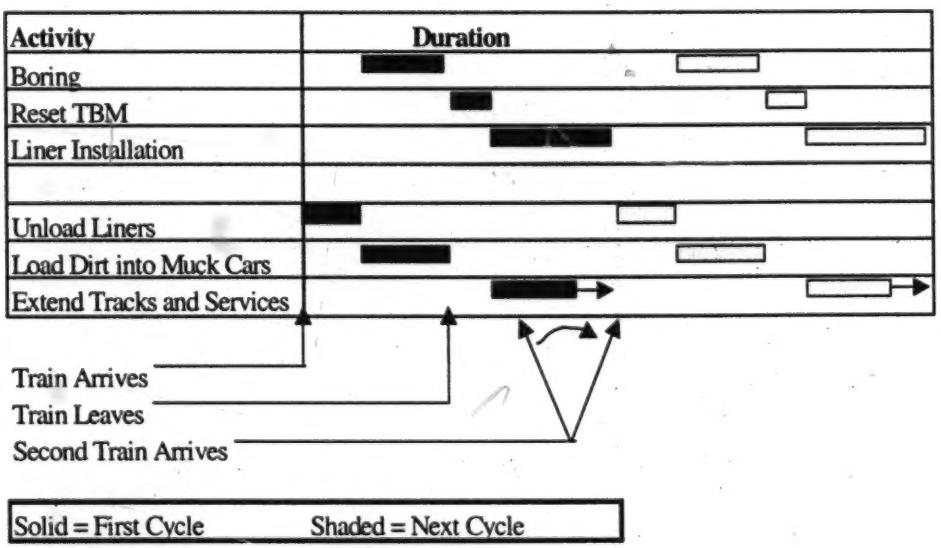
The tunneling simulation template has several modeling elements. The original TBM template (one-way tunneling) contains nine modeling elements (Figure 3-9a). The enhanced TBM tunnel template (Figure 3-9b) which models two-way tunneling contains fourteen elements. The enhanced template includes four modeling elements serving both directions and five elements unique to each side. Each modeling element may contain input parameters, outputs and statistics. Further, each modeling element can obtain input values from elements of the same level or from parent elements, and report the outputs and statistics to the various elements. All the modeling elements and their inputs are listed in Table 3-2. These tunnel elements can be divided into four categories to illustrate the purpose for including them in the template. The detailed descriptions of each of the modeling element are explained later in the chapter.

(a)


Activity
Duration
Hoist muck car to Ground Level
Dump Dirt, Clean and Lower the Car
Load Material Car with Liners *
Lower the Material Car to Undercut *
First Train Arrives
First Train Leaves
Second TrainArrives
Solid = First Cycle
Shaded = Next Cycle

** These activities can be performed before muck cars are unloaded, if time permits.*

(b)



** The leaving of the train depends on the capcity of muck cars.*
Refer the next section for modeling parameters and processes for detail.

Figure 3-8: Repetitive construction processes at (a) shaft and (b) tunnel face

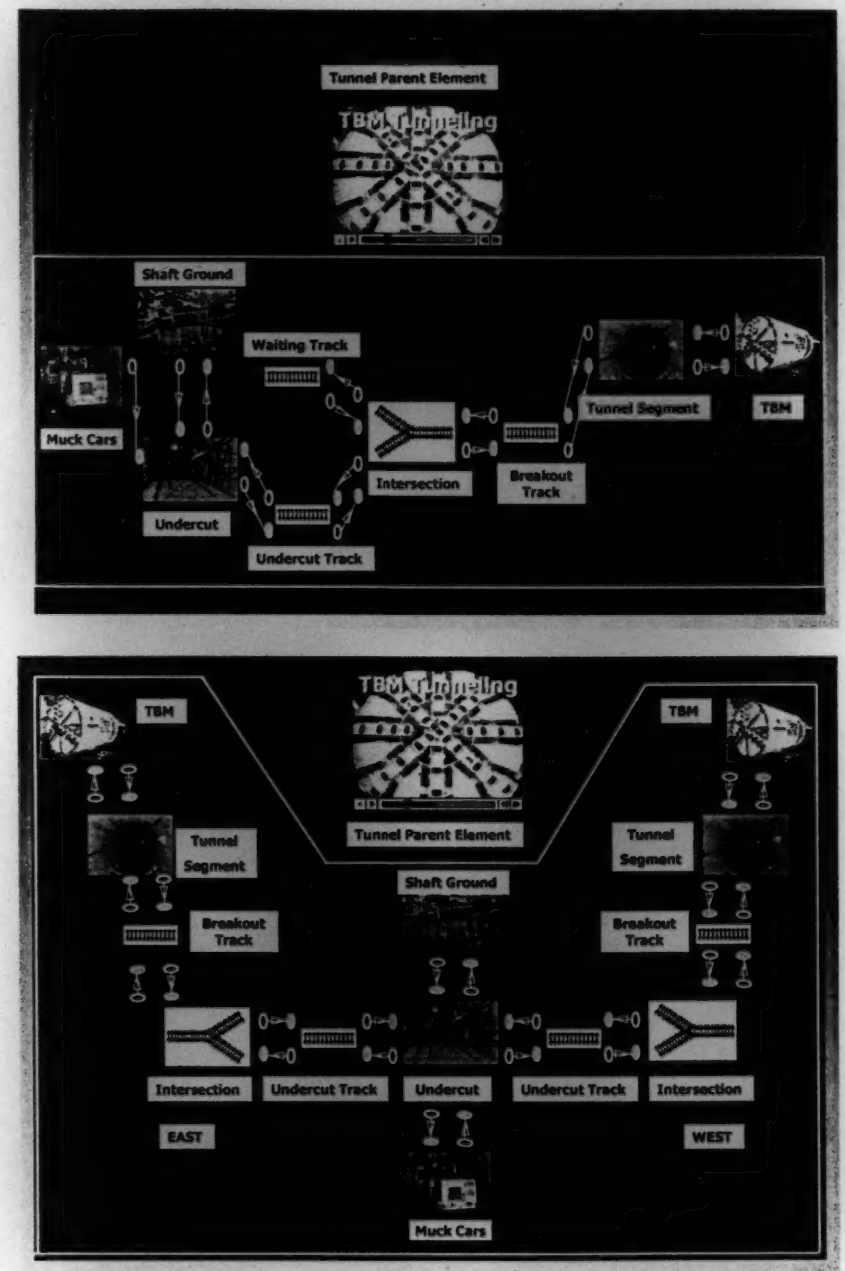


Figure 3-9: Modeling layouts of the (a) one-way and (b) Two way tunnel templates

Table 3-2 Modeling Elements and Input Variables

	Modeling Element	Description of the Input Variable	Quantitative Variable Deterministic (D) or Stochastic (S)		Subjective Variable
			D	S	
1	Main Tunnel Parent	Total tunnel length (meters)	X		
		TBM Type			Select from a list
		Shift Length (minutes) per day	X		
		Mobilization Time at the start of the day (minutes)		X	
		Buffer Time at the end of the day (minutes)		X	
		Break for Lunch			Yes/No
		Implement an intermediate undercut			Yes/No
		TBM boring cost: Labour ($/hour)		X	
		TBM boring cost: Equipment ($/hour)		X	
		Liner installation cost: Labour ($/hour)		X	
		Liner installation cost: Equipment ($/hour)		X	
		Pre-Cast liner installation cost: Material ($/meter)		X	
		Rib & Lagging liner installation cost: Material ($/meter)		X	
		Hoisting cost: Labour ($/hour)		X	
		Hoisting cost: Equipment ($/hour)		X	
		Train operators cost: Labour ($/hour)		X	
2	Muck Car	No. of trains	X		
		No. of muck cars (Dirt)	X		
		No. of muck cars (Material)	X		
		Muck car capacity (m^3)	X		
		Train speed - to tunnel (kilometers/hour)		X	
		Train speed - from tunnel with dirt (kilometers /hour)		X	
		Cost of train ($/hour)		X	
		Cost of material car ($/hour)		X	
		Cost of muck car ($/hour)		X	
		If 2 trains, the second train releases when bored length reaches (meters)	X		
3	Shaft-Ground	Lifting method of dirt			Select from a list

Table 3-2 Cont. Modeling Elements and Input Variables

	Modeling Element	Description of the Input Variable	Quantitative Variable Deterministic (D) or Stochastic (S) D	S	Subjective Variable
4	Shaft Undercut	Loading duration of liners (minutes)		X	
		Depth of the shaft (meters)	X		
		If an intermediate undercut is implemented, the distance to the intermediate undercut from the main shaft (meters)			Yes/ No
		Hoisting (both up and down) duration per 10 vertical meter increments - per 1 dirt car – (minutes)		X	
		Hooking, dumping, cleaning and unhooking duration per 1 dirt Car (minutes)		X	
5	Undercut Track				
6	Intersection				
7	Waiting Track				
8	Breakout Track				
9	Tunnel Segment	Length (meters)	X		
		Soil Type			Select from a list
		Method of liner installation			Select from a list
10	TBM	TBM diameter (m)	X		
		TBM reset time (minutes)		X	
		Stroke length - pre-cast liners (meters)	X		
		Stroke length - rib and lagging (meters)	X		
		Unloading time of liners (minutes)		X	
		Liner installation time -pre-cast liners (minutes)		X	
		Liner installation time - rib and lagging (minutes)		X	

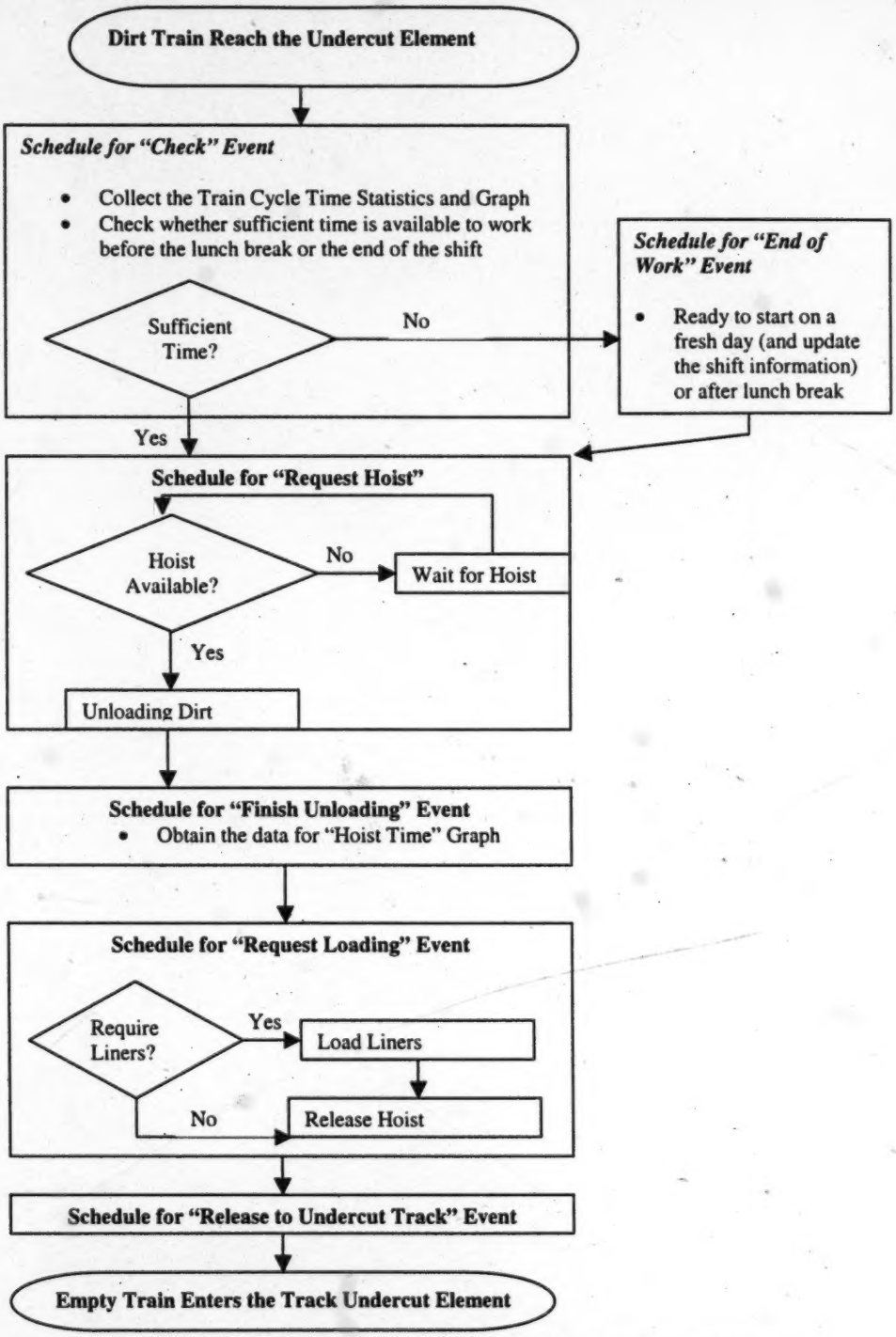

Dirt Train Reach the Undercut Element
Schedule for "Check" Event
Collect the Train Cycle Time Statistics and Graph
Check whether sufficient time is available to work before the lunch break or the end of the shift
Sufficient Time?
No
Yes
Schedule for "End of Work" Event
Ready to start on a fresh day (and update the shift information) or after lunch break
Schedule for "Request Hoist"
Hoist Available?
No
Wait for Hoist
Yes
Unloading Dirt
Schedule for "Finish Unloading" Event
Obtain the data for "Hoist Time" Graph
Schedule for "Request Loading" Event
Require Liners?
Yes
Load Liners
No
Release Hoist
Schedule for "Release to Undercut Track" Event
Empty Train Enters the Track Undercut Element

Figure 3-10: Scheduling of events in the shaft undercut element

(1) *Entity Generation and initialization of properties to entities. Muck car* element generates the trains according the parameters defined by the user.

(2) *Decision-making*. There are three elements; *tunnel parent*, *shaft ground*, and *tunnel segment* that provide information for making various decisions related to the tunnel construction operations. For example, the *tunnel segment* element chooses the length of each segment and defines the soil properties for each segment, information that is then accessed by various other elements for decision-making during simulation.

(3) *Process Operations*. The *shaft-undercut* element and *TBM* element include many work processes. The entire work processes have been programmed under these two elements. Figure 3-10 briefly outlines the scheduling of the events in the *shaft-undercut* element. The simulating logistics of a modeling scenario could be written using a visual basic code. Alternatively, the modeling scenarios could be simulated by creating its child elements inside the main modeling elements that will eventually reduce the object oriented programming code for each scenario.

(4) *Movement of Entities*. The *undercut track*, *intersection*, *waiting track* and *breakout track* elements check various actions and operations in the model and maneuver the traffic of the trains.

3.6.2 Features of the Tunnel Template

The TBM tunnel template utilizes various functional features built into the Simphony engine. The following are the unique features in the tunnel template.

(1) *Cost Planning Engine*: Tunnel template became the first SPS template that incorporates the cost planning information based on the simulation. The planning behavior of the tunnel template defines how a given modeling element (for example TBM element) transforms its simulation results into a project plan that includes schedule, production, cost forecast, and resource utilization information. The cost planning module of the tunneling template tracks down the actual activity time duration, productivity, cost figures (including direct costs, indirect costs and even overtime costs based on shift length), and cash flow information instantaneously when the events related to activities are simulated. The user inputs the unit costs or hourly costs. This cost planning module is very useful in analyzing alternative proposals for tunnel construction operations without referring to another planning or estimating program.

(2) *Custom Built Reports and Statistics*. The designer-built outputs and statistics generate the productivity of the activities, waiting times of the trains to obtain resources, train cycle times, waiting times of the resources, and duration for certain activities. These reports help the users to make several decisions regarding the tunnel construction processes, which cannot be determined arbitrarily.

(3) *Simulation of hypothetical work conditions*. Most of the simulation applications run for various time units continuously. The tunnel template is one of the first to among SPS templates that attempts to simulate the hypothetical work pattern at site, the unproductive time of each day at the end of the shift, and suspends the work for lunch breaks and the end of shift. The productivity and cost figures are updated per shift. The user can specify the shift length and the decision to stop for lunch breaks.

3.6.3 Modeling Elements, Input Parameters and Processes

There are various modeling elements in the tunnel template. Design of graphical user interfaces in the modeling elements to depict the construction options (or the meaning of the modeling element within the application) or the construction layout allows the experienced end user of tunneling who is not familiar in simulation to create a model with ease

The *tunnel parent* element is the main hierarchical element of the template. Many input factors that are required globally for each modeling element are included in this element. Further, various global outputs and statistics generated from various other elements are reported to this element. The tunnel element has the following input parameters (see Table 3-2) for simulation: tunnel length to be bored, TBM type (open face/ closed face), shift length per crew, mobilization time at the commencement of each shift length (or day), buffer time (the time between closing time of the shift and the end of shift) at the end of the day, the decision to stop work for lunch, and the decision to implement an intermediate undercut. At the end of the shift, the simulation model determines whether it is possible to bore another stroke length of the tunnel or install the liners after the tunnel portion has been bored within the buffer time specified. If the work is stopped for lunch, productivity is affected by the stoppage of work before lunch and re-mobilization time before construction starts after lunch. The template requires a few other input parameters for cost forecasting purposes as listed in Table 3-2. Figure 3-11 shows a sample of the main modeling element of the tunnel template and its input parameters, statistics and project plan information.

The *muck car* element has parameters related to trains and muck cars as listed in Table 3-2. When two trains are utilized for TBM tunneling, the second train is only released when the tunnel reaches a certain distance. This is to avoid congestion at the undercut area due to the initial confined space of the tunnel. The second train is usually introduced when the tunnel reaches 40-60 meters. The tunnel boring operation changes depending on the total capacity of the muck cars. According to City of Edmonton tunnel operations, a close-face TBM only bores one meter of tunnel before installing the pre-cast segment liners irrespective of the soil type. If the total capacity of the muck cars is greater than the bank volume of one meter of dirt, the loaded train leaves to shaft as soon as the TBM finishes boring one meter of tunnel. If the total capacity of muck cars is less than the bank volume of one meter of dirt, the train leaves as soon as its cars are filled, irrespective of whether the TBM has bored one meter. The TBM is stopped until a new train arrives at the tunnel face. If the train is partially filled when the TBM achieves the required meter, it waits until the TBM installs the liners for the bored meter. The rest of the muck cars are filled in the next boring cycle. The train is the main entity of the model and not considered as a resource. In the two-way tunneling operation, the second side of the trains are released when a certain length of the first side has been achieved.

The *shaft-undercut* element obtains the inputs for unloading and handling times of dirt cars from undercut to shaft, and the loading time of liners from shaft to undercut. The user can specify the depth of the shaft, the unloading time per car based on 10 meter height, and other miscellaneous times (hooking the car to the hoist, unhooking the car from the hoist, dumping time per dirt car, and cleaning time per car). If an intermediate undercut is utilized, the length of the intermediate undercut from the main undercut is

another input in the original template. In the two-way tunneling template, the traffic maneuvering time at the undercut when a dirt-filled train reaches the undercut is an input parameter. The crane is one of the resources of the model. The shaft-ground element has been populated with different hoisting resources from which the user chooses.

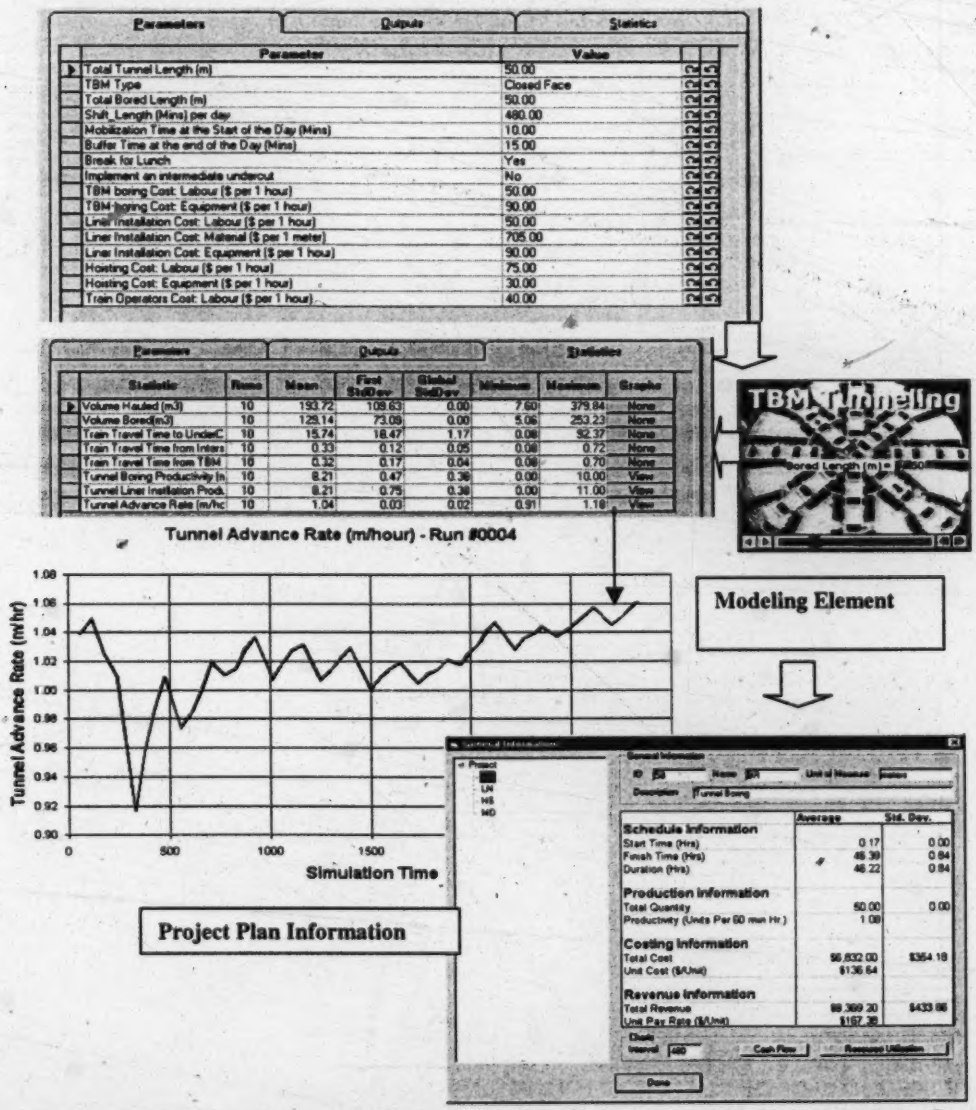

Parameters
Outputs
Statistics
Parameter
Value
Total Tunnel Length (m) 50.00
TBM Type Closed Face
Total Bored Length (m) 50.00
Shift_Length (Mins) per day 480.00
Mobilization Time at the Start of the Day (Mins) 10.00
Buffer Time at the end of the Day (Mins) 15.00
Break for Lunch Yes
Implement an intermediate undercut No
TBM boring Cost: Labour ($ per 1 hour) 50.00
TBM boring Cost: Equipment ($ per 1 hour) 90.00
Liner Installation Cost: Labour ($ per 1 hour) 50.00
Liner Installation Cost: Material ($ per 1 meter) 705.00
Liner Installation Cost: Equipment ($ per 1 hour) 90.00
Hoisting Cost: Labour ($ per 1 hour) 75.00
Hoisting Cost: Equipment ($ per 1 hour) 30.00
Train Operators Cost: Labour ($ per 1 hour) 40.00
TBM Tunneling
Tunnel Advance Rate (m/hour) - Run #0004
Tunnel Advance Rate (m/hr)
Simulation Time
Modeling Element
Project Plan Information

Figure 3-11: Tunnel parent element (inputs, outputs, statistics) and project plan

The *undercut track*, *intersection*, *waiting track* and *breakout track* elements check various actions and operations in the model and maneuver the traffic of the trains. In the original tunnel template, if the first train is inside the tunnel and the second train has finished unloading dirt, the second train travels to the *intersection* and backs up to the *waiting track*. When the loaded train comes out of the tunnel and travels to the *undercut*, the waiting train at the *waiting track* leaves to the tunnel face. In two-way tunneling template, excavation is performed for two opposite directions using two tunnel-boring machines and one shared hoist. The traffic movement for using two trains for each side has been modified considering all the possible events that could happen in a bottleneck situation

The simulation model allows the user to add many *tunnel segments* to the model depending on the soil properties. For example, if the tunnel to be bored is 275 meters long in clay soil and there are 35 meters of bedrock in the tunnel to be bored starting at the 100th meter of the tunnel, the user can add three segments of *tunnel segment* as in Figure 3-12. The first tunnel segment is connected to the *Breakout track* and the last tunnel segment is connected to the *TBM* element. The type of soil and the length of the tunnel section are the input parameters. The simulation model determines the tunnel penetration rate (boring rate) and the swell factor of the soil based on the input. This modeling element was modified allowing the user to input the compositions of the soils and the lining method for each segment (Figure 3-13).

The input parameters for *TBM* element are TBM size, liner installation method, TBM re-set time, unloading time of liners, and liner installation time. The simulation model

determines the availability of time and the need to unload liners before the next boring cycle begins. TBM is a main resource in the model.

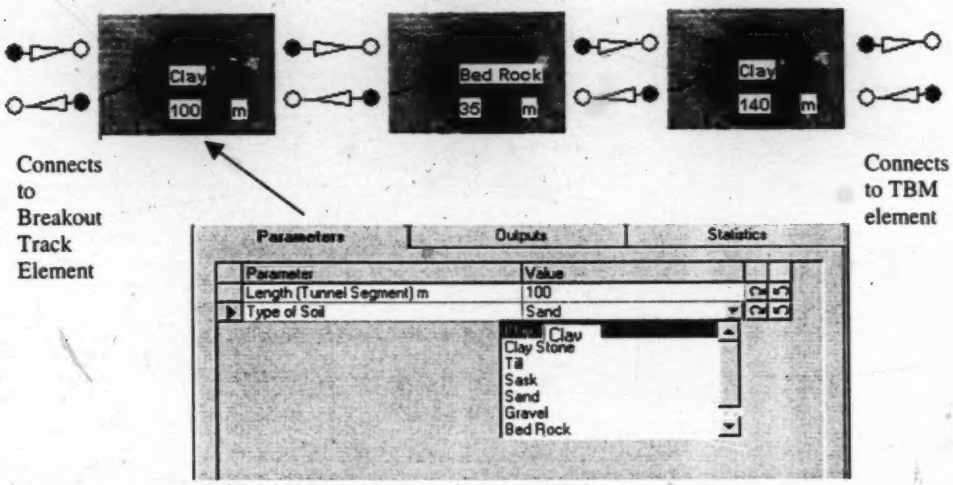


Figure 3-12: Different soil properties in Tunnel segments and connections to the adjoining elements

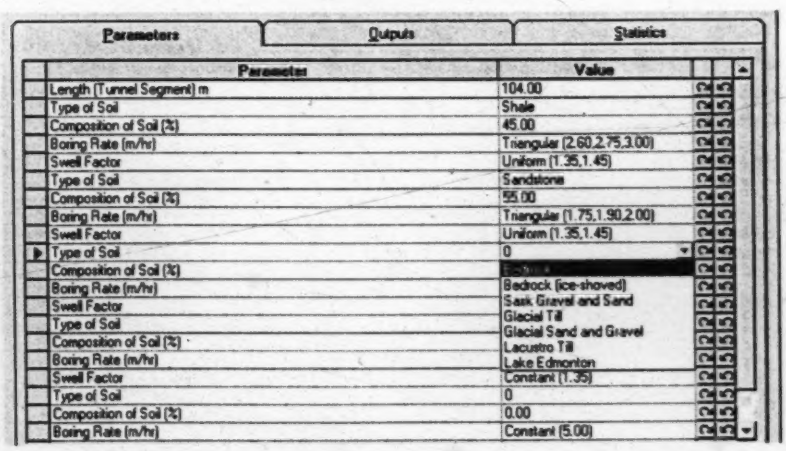


Figure 3-13: Modified Soil Segment Modeling Element

3.6.4 Modeling Outputs and Statistics

In addition to Simphony's standard graphical reports and statistics, there are various designer-built graphical reports and statistics in the tunneling template specially designed to help the end users to make decisions for construction alternatives. The designer-built outputs and statistics are reported to various elements of the model. The outputs and statistics can be divided into the following sub-sections (Ruwanpura et al. 2000c).

1. Productivity and tunnel advance rate. The tunnel template predicts the tunnel advance rate (meters/hour) and the productivity of boring, liner installation, material hoisting, and train movement both graphically and statistically.
2. Resource Utilization: The utilization graphs for main resources, such as TBM and Crane, can be obtained from the template along with queue length and the waiting times to obtain the resources.
3. Project Management information such as cost, schedule and cash flow forecasting: The cost planning module of the tunneling template tracks down the actual activity time duration, productivity, cost figures (including direct costs, indirect costs, and overtime costs based on shift length), and cash flow information instantaneously when events related to activities are simulated.
4. Various other statistics: Other statistics, such as the waiting time of train at tunnel face and during traffic movement, train cycle time, and dirt hoisting times, are graphically illustrated in the template.

3.7 Developing and Testing Strategies of the Tunnel Template

The basic Simphony engine was released in March 1999. After studying the tunnel construction work performed by City of Edmonton, a preliminary proposal was forwarded to the management of City of Edmonton that included the various attributes, factors, and methods that could be considered for the tunnel template. The method of tunneling (hand or TBM tunneling), dirt removal process, liner installation, and traffic layout were the major factors. The developers of the template and the management of City of Edmonton decided to limit the preliminary scope of the tunnel template to closed face TBM tunneling using pre-cast concrete liner installation.

The model developers and City of Edmonton management observed the conceptual model before the actual design stage of the template using Simphony. The use of several modeling elements, as explained in Section 3.6, and the sequence of the tunnel operations are just two examples of the collective design efforts made by model developers and the management of City of Edmonton. After the basic template had been developed and tested in June 1999, a few embellishments were made to the tunnel template based on suggestions from the management of City of Edmonton to apply for project planning of a tunnel project. The following are the major improvements which are reproduced from Ruwanpura et al. (2000b and 2000c).

a) Model the hypothetical work behaviours in construction such as stopping the work at the end of the shift and suspending the work for lunch breaks as explained in Section 3.6.2.

b) Implementation of an intermediate undercut: It is a known fact that, on longer tunnels, the tunnel advance rate and the production per day diminish when the tunnel length increases. Therefore, the template has been modified to allow an addition of an intermediate undercut to facilitate switching of trains for the purpose of improving the dirt removal.

c) Two-way tunneling: The tunnel template has been embellished to model two-way tunnel construction operation. In this option, excavation is performed from two opposite directions using two tunnel-boring machines. The user can decide when to start the second side of the excavation.

The application of simulation has been a very challenging task for model developers and the staff of City of Edmonton. The tunnel template has been used for testing purposes before applying it to actual construction scenarios. The staff at City of Edmonton suggested several new ideas to modify the template at the testing and application phases. Since the application is for a real-life construction project, there was more insight to the development of the template from City of Edmonton. The tunnel template has been tested several times using different data inputs to identify the critical input parameters before testing alternate options. The following have been identified as the critical input parameters:

(1) Type of soil (and the penetration rate of boring)

(2) Liner installation time

(3) Swell factor of soil

(4) The capacity and number of muck cars

(5) Train speed

The dirt removal times at the shaft have been found to be non-critical in one way tunneling when two trains are in operation. The capacity of the muck cars is the most critical issue according to the results (Ruwanpura et al. 2000a). If the capacity is less than the volume to be hauled for one stroke length (1 meter) of the TBM, the productivity of the entire tunneling operation is reduced. The capacity of muck cars has been optimized to haul the dirt. The TBM manufacturers were contacted to identify the TBM efficiency under different soil conditions. Those theoretical efficiency factors and the tunnel personnel's comments have been considered in determining the activity durations. Further, data collected from two tunnel construction projects in Edmonton was useful in justifying some of the data provided by the tunnel personnel. Most of the parameters as listed in Table 3-2 are stochastic. Based on the comments made by the tunnel personnel and the observations made during data collection at site, the duration for activities was applied using various known distribution types and input them into the template. For example, the liner installation time was assumed to be uniformly distributed between 15 and 20 minutes, the train speed time was assumed to be triangularly distributed with a low of 5 km/hour, a mode of 7 km/hour and a high of 10 km/hour.

3.8 Conclusions

The design and development of the special Purpose simulation tool has been presented for the analysis of tunnel construction projects. The success of the design and development was due to the flexibility of the modeling engine and the integrated design layout. The graphical user interfaces and the high level modeling constructs allowed the users who were not familiar with the simulation theory to build sophisticated models and experiment with different options to optimize the overall development of the template. The adaptability of hypothetical work conditions such as breaks for lunches and end of shifts provided a true picture of a real system. This SPS tool became very handy by incorporating the cost-planning engine built with Simphony, to produce the cost, schedule, productivity, cash flow and resource utilization based on the simulation results. The ability to model for several scenarios without changing the developer's code or the base of the tool is another advantage of this tool.

The model designers faced many challenges during the design, development, and implementation of the tunnel simulation. Non-availability of numeric data for various activity durations in tunneling, and the lack of experience of tunneling process and limitations in the Simphony engine were the preliminary challenges during the design and development phase. From the City of Edmonton's perspective, there was some skepticism from many who were not familiar with simulation, and could not visualize the potential benefits of applying simulation to tunneling. Once preliminary results based on the original tunnel template were presented, their interest and acceptance grew with each phase of the development. The incorporation of cost planning module with the simulation allowed easy comparison of the construction option using comparative cost, schedule and

productivity analysis. The development of two-way tunneling has provided many new ideas to the engineering staff, prompting them to make more suggestions, which finally helped to enhance the model for new options. The identification of the critical factors that affect the tunnel productivity also provide an opportunity for the model developers and engineers at City of Edmonton to evaluate more options for testing and validation purposes.

Chapter 4: Application of Tunnel Simulation Template for Tunnel Construction Projects[1]

4.1 Introduction

This chapter presents the application of the tunnel simulation template for several purposes as outlined below. Each of these applications has led to improvements to increase the capabilities of the template. The tunnel template described in chapter 3 provides the following practical benefits.

1. The template can be used to model any hypothetical construction alternatives for utility tunnel construction and thereby allowing the industry personnel to evaluate alternate construction options for tunneling expeditiously. This helps the end users to use for project planning and decision-making using simulation to plan the sequence of work activities, declare the method of operation, select the suitable resources for the given project, analyze the production of the system and avoid possible bottlenecks before commencing actual construction.
2. The template can also be used during construction to feed input for control purposes. The collection of data in the same project can be applied to generate the productivity for the rest of the project. Hence, this tool is not only used as a planning tool. This enables the planners and engineers to observe productivity and resource utilization levels and conduct additional testing to improve the efficiency of the system using the available resources during construction.

[1] This chapter mainly contains extracts from the paper "Special Purpose Simulation Templates for Tunnel Construction Operations" published in the Canadian Journal of Civil Engineering, CSCE, 28(2), 222-237.

3. The use of cost planning module can assist the planners, engineering and estimators to prepare a preliminary range estimate of a tunnel construction project. This could be further extended as a powerful tool for estimating alternatives during bidding.

The following sections of the chapter discuss the various applications of the tunnel simulation template and its contributions in different aspects. The expected major contributions stated above are witnessed in each of the application described below.

1. Testing the template for tunnel construction projects by changing different resources, and setting up options for undercut and shaft, which was documented in AbouRizk et al. (1999). This part is documented in Section 4.2.
2. Evaluating various alternatives at the project planning stage of a tunnel construction project in Edmonton (Er et al. 1999 and Er et al. 2000). A detailed analysis of the project planning application is presented in Section 4.3.
3. Evaluating two scenarios of bidding analysis and finally deciding on one scenario, based on the outputs of the simulation model (Ruwanpura et al. 2000c). This bidding analysis is briefly stated in Section 4.4.
4. Justifying the observation that the uncertainty of soil conditions can cause inaccuracies in the prediction of productivity in tunnel construction (Ruwanpura 1999). The discussion of this observation is presented in Section 4.5.

The final discussion of the application of tunnel template for several purposes is explained in Section 4.6.

4.2 Testing the template for tunnel construction projects by changing different parameters

The preliminary testing of the tunnel simulation template was performed using available historical data and the experience of the personnel at the City of Edmonton to identify whether the tunneling processes have been modeled properly. Table 4-1 depicts the historical data obtained to test the template with the specifications of 2.3 meter diameter tunnel using LOVAT M100 TBM and two trains in good clay soil. The tunnel is supported with pre-cast segment liners.

Table 4-1: Historical Input Parameters for Testing

Input Parameter	Value
Train Speed (kmph)	Uniform (3.00, 4.00)
Unloading Dirt for Muck Car (1.9 m3) - Mins	Triangular (3.00,3.50,4.00)
Unloading Dirt for Muck Car (0.75 m3) - Mins	Triangular (2.75,3.00,3.50)
No. of Muck Cars - Small Capacity	6
No. of Muck Cars - Large Capacity	4
Loading of Liners from Shaft to Undercut - Mins	Constant (4.00)
TBM Penetration Rate for Clay (m/hr)	Uniform (4.00, 4.25)
TBM Reset Time - Mins	Uniform (1.00, 3.00)
Unloading of Liners from Trains - Mins	Constant (4.00)
Liner Installation Time	Triangular (15.00,16.00,18.00)
Shift Length - Mins	480
Mobilization time at the commencement of each day - Mins	15
Buffer Time at the end of the day - Mins	15
Break for Lunch	Yes

4.2.1 Test # 1: Comparison of Results by Changing the Site Set-up at Undercut

The availability of site space is a governing factor for tunnel production. If the space for shaft, undercut and tail tunnel is limited, the project manager prefers to use a smaller

setup which requires smaller capacity muck cars that are easier to be hoisted using a small crane. The alternative is to use larger capacity muck cars, which are hoisted using a comparatively larger crane. The tunnel template was used to test the output results for both. Table 4-2 outlines the results obtained for the first 45 days. Figures 4-1 and 4-2 illustrate the average Tunnel Advance Rate (meters/hour) for both cases. The simulation results show that the smaller setup generates a less productive tunnel advance rate. The TBM utilization is also reduced in the smaller set up. The crane utilization increased in the smaller set up due to higher frequency of muck car handling.

Table 4-2: Statistics for Tunnel Simulation – Test # 1

	Large Muck Cars	Small Muck Cars
Tunnel Length (m)	560	361
Days	45	45
Average Tunnel Adavance Rate (m/hr)	1.56	1.00
Average TBM Utilization	82.80%	52.30%
Average TBM Queue Length - Mins	0.14	0
Average TBM Waiting Time - Mins	1.9	0
Average Crane Utilization	39.65%	49.05%
Average Crane Queue Length - Mins	0	0.03
Average Crane Waiting Time - Mins	0	0.78

(a) (b)

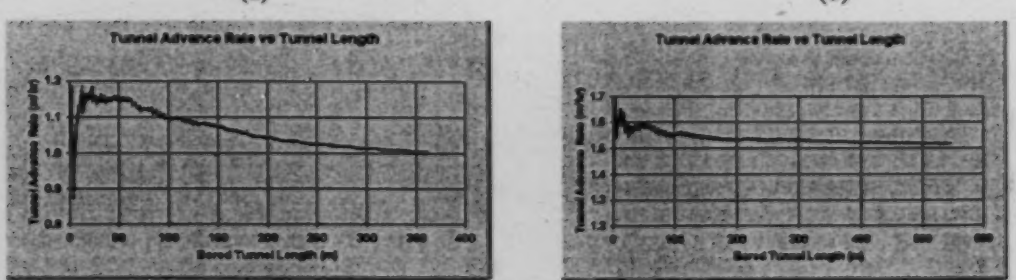


Figure 4-1: Tunnel Advance Rates for Test # 1 (a) Smaller Set–up (b) Larger Set-up

4.2.2 Test # 2: Encountering Different Soil Conditions in the Smaller Set up

At this testing stage, different soil properties can be added on an arbitrary basis to the tunnel template. The rate of tunnel production varies depending on the soil conditions. In this modeling scenario, *Bed Rock* is encountered for 20 m when the tunnel reaches 30 meters. The soil for all the other areas is soft clay. The total tunnel length is 100 m. Figure 4-2 shows the tunnel advance rate for this scenario. The tunnel advance rate is considerably reduced when boring in *Bed Rock*.

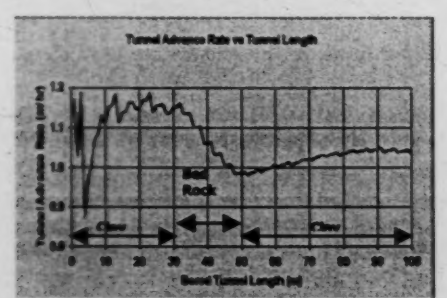


Figure 4-2: Tunnel Advance Rate with different soil conditions

The objective of the analysis of the simulation model was to estimate the tunnel advance rate and the optimization of the resources. Further, the effect of other variables on tunnel advance rate due to has been analyzed. The results show that the tunnel advance rate is inter-dependent on various factors and activities in the tunneling operations. The resources can be optimized if both cycles of tunnel face and shaft operations are analyzed and adjusted to achieve the maximum efficiency.

4.3 Project Planning and Decision Analysis for First Stage (SW1) of South Edmonton Sanitary System (SESS) Tunnel Construction Project

The tunnel simulation template was used extensively for project planning of the first stage of the SESS project. The exact location of the tunnel and its components are explained to illustrate the concepts clearly. The following analysis explains in detail the various phases of project planning of the tunnel project using simulation and how the final construction operations method was selected based on the results generated from the tunnel template for the project. The simulation analysis was conducted in three phases commencing from conceptual design stage to the detailed design and construction stage. The phase three analyses was conducted after the City of Edmonton has finalized the construction options based on the results on phase 1 and 2. The following are the three phases.

(1) *Phase 1*: Original scope of work was for a 2.9 meter diameter 1600-meter tunnel. In this stage, the main concern was the optimization of the muck removal during tunnel excavation.

(2) *Phase 2*: Revised scope of work for the same tunnel but using a 2.3 meter diameter and 2400-meter long. Three options were considered, which are explained in Section 4.3.3

(3) *Phase 3*: Re-revised scope of work for the same tunnel using a 2.3 meter diameter and 2500-meter long tunnel. City of Edmonton reviewed a total of five tunnel

construction methods during this design stage, which are described in Section 4.3.1 Some of these alternatives have been tested using the tunnel template In addition to the three options evaluated under stage 2, a new option was considered to excavate the tunnel from both directions simultaneously.

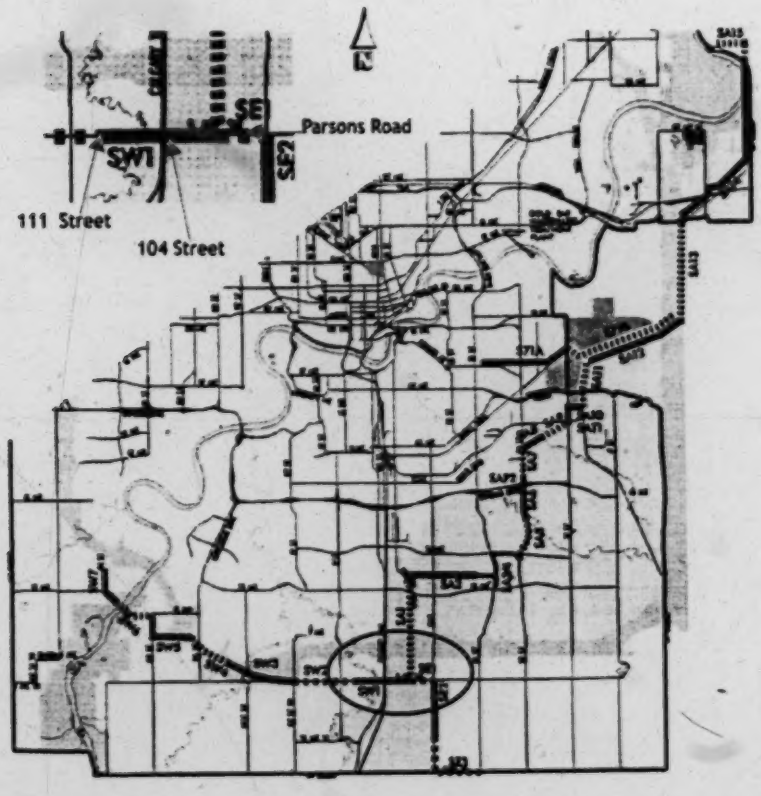


Figure 4-3: SW1 Tunnel in SESS Project

4.3.1 Final Construction Alternatives for SW1 Project

The SW1 tunnel is located under Ellerslie Road between Parsons Road and 111 Street (Figure 4-3). The final scope consists of a sewer lift station at Parsons Road, which is linked to a 2500-meter long tunnel that terminates at 111 Street. The tunnel receives the sanitary flows at Parsons Road, 104 Street and 111 Street through drop structures. The finished diameter of the tunnel is 2344 mm. Tunnel depth varies from 40 meters at the east end (Parsons Road) to about 35 meters at the west end (111 Street). The eight boreholes revealed that the tunnel was to be constructed in bedrock, which primarily contains clayshale, siltstones and sandstones with compressive strength between 50-90 MPa. During the conceptual design phase of the project, the management committee decided that City of Edmonton would construct the tunnel. City of Edmonton reviewed a total of five tunnel construction methods during the preliminary design stage, which are described below. Some of these alternatives have been tested using the Simphony tunnel template.

Alternative 1 - Continuous tunneling from Parsons Road (East) to 111 Street (West)

The main working shaft would be set up at the lift station site immediately north of Ellersilie Road and east of the future Parsons Road. The shaft and undercut would be modified as needed for the proposed lift station. Tunneling operations would proceed in a westerly direction with down-holes spaced up to approximately 550 m apart. Tunneling would terminate in the vicinity of 111 Street, with provision for a future connection to

next phase. The shafts at 104 Street and 111 Street would be modified to accommodate drop structures which would be the only connection points along the tunnel.

Alternative 2 - Tunneling From Parsons Road (East) to 111 Street (West) with Passing Track at 104 Street.

This alternative is similar to Alternative 1 except that a passing track would be constructed in the vicinity of 104 Street (west of Calgary Trail). The purpose of the passing track is to allow an additional train to park closer to the Tunnel Boring Machine (TBM). This would minimize the idle time of the TBM while waiting for muck cars. The loaded muck cars would travel back to main working shaft at Parsons Road for surface disposal.

Alternative 3 - Tunneling From Parsons Road (East) to 111 Street (West) with Muck Removal at 104 Street.

This is similar to Alternative 1 except that an intermediate working shaft would be excavated at 104 Street for muck removal. This would reduce the travel distance of the muck cars, minimizing the TBM idle time. The working shaft at Parsons Road could also be available for lift station construction as soon as the 104 Street shaft is set up, thereby allowing the lift station to be constructed earlier, compressing the overall construction schedule.

Alternative 4 - Tunneling from a Common Working Shaft at 104 Street East to Parsons Road and West to 111 Street using one TBM

This alternative involves setting up the main working shaft at 104 Street. The TBM tunneling would proceed in an easterly direction to Parsons Road. The TBM would be removed from the shaft at Parsons Road and reinstalled at the main shaft at 104 Street. The balance of the tunnel would be constructed towards the westerly direction ending at 111 Street. The advantage of this alternative is that the tunneling length in either direction is relatively short and optimal for train travel time. In conjunction with this alternative, a crawler conventional crane is considered instead of a derrick type hoist. This facilitates the reinstalling of the TBM without dismantling and reinstalling the superstructure for the derrick hoist.

Alternative 5- Same as Alternative 4 but using Two TBMs

This alternative is the same as Alternative 4 except that two TBMs would be used concurrently, one tunneling east to Parsons Road while a second tunnels west to 111 Street. It was decided that the west leg would be tunneled first due to its longer distance. This alternative became feasible in October 1999 when Design & Construction became aware of a refurbished TBM (M100) available at an affordable price. Tunnel simulation analysis further ratified the idea, which is explained in the next section.

4.3.2 Simulation Analysis of SW1 Project – Phase One

The preliminary scope of the SW1 tunnel comprised the construction of a 2.9-meter diameter (finished diameter with pre-cast concrete segment liners) and 1600-meter long

tunnel in sandy soil. City of Edmonton estimators prepared preliminary conceptual estimates based on the previous experience of similar projects (Ruwanpura et al. 2000a). According to the conceptual project plan and estimates prepared by the City of Edmonton estimators, the boring and liner installation could be achieved with an average of 5-7 meters/shift. The conceptual estimates predicted a minimum basic cost of $ 1,631.14 per meter for boring, liner installation, hoisting and dirt removal. The preliminary planned duration was 229 shifts of 8 hours each when the assumed productivity is 7 meters/shift. City of Edmonton's Drainage Service, Design and Construction Division evaluated the conceptual plan and the estimates using the TBM tunneling template for two options. The results generated from the TBM template showed that the intended productivity of 7 meters/shift assumed by the estimators could not be maintained throughout the project. The template generated an average productivity of 4.56 meters/shift. The Simphony simulation engine allows applying either deterministic or stochastic values for input variables (Hajjar and AbouRizk 1999). The highest productivity (5-8 meters/shift) could be maintained for about 130 shifts. The average cost per meter was $ 1,770.14 for 355 shifts. Because the total capacity of the muck cars was far below the volume to be hauled for one meter of excavation, the City of Edmonton's Drainage Service, Design and Construction Division suggested changing the muck car system. City of Edmonton has 4.60 cubic meters (m^3) capacity mine cars, which are used to construct very large diameter tunnels. The original proposal was to use five 1.70 m^3. The alternate proposal was to use three 4.60 cubic meters cars.All the other equipment was not changed as it can be used for both proposals. The results were generated after simulating both the original and the alternate options. The results of the proposals and the conceptual estimate cost

data are shown in Table 4-3. Simulation study presented that the alternate proposal is the best between the two in terms of the cost and the productivity.

Table 4-3: Simulation results of Phase 1, comparing conceptual estimates

	Cost ($/meter)	Productivity (m/shift)	Duration (No. of shifts)
Conceptual Estimate # 1 using five 1.70 m^3 muck cars	1,631.64	7	229
Conceptual Estimate # 2 using five 1.70 m^3 muck cars	1,928.45	5	320
TBM Simulation Template using five 1.70 m^3 muck cars (original)	1,770.14	4.6	355
TBM Simulation Template using three 4.60 m^3 muck cars (alternate)	1,500.19	7.4	218

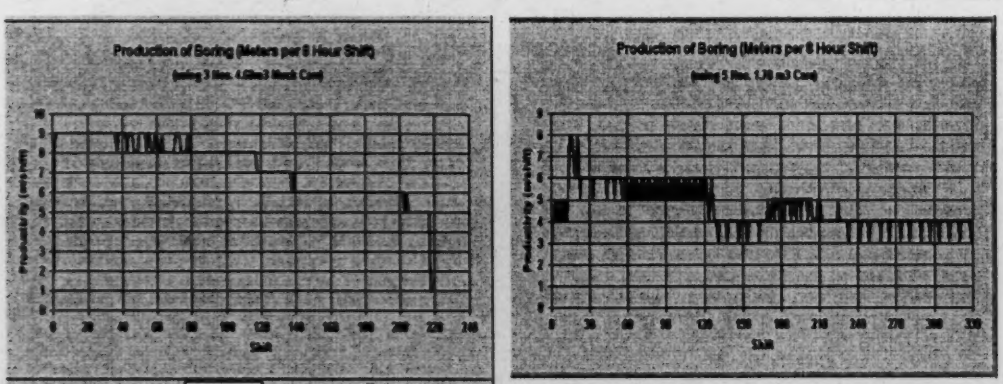


Figure 4-4: Productivity of Boring for Original (right) and Alternate (left) Proposals

Figure 4-4 clearly shows that the production of boring in the alternate proposal is as high as 9 meters/shift initially and drops down to 5 meters/shift at the end. There is a

gradual reduction of the productivity of boring in the alternate proposal compared to the original proposal. The simulation statistics in Table 4-4 indicate that the original proposal results in less utilization of the main resources. The preliminary test of the simulation results helped to investigate different proposals without embarking on a set of specifications previously used for similar types of tunnel projects

Table 4-4: Simulation Statistics from TBM Tunneling Template – Stage 1

	Original Proposal	Alternate Proposal
Average TBM Utilization	42.00%	70.05%
Average TBM Queue Length - Mins	0	0.07
Average TBM Waiting Time - Mins	0	1.87
Average Crane Utilization	37.90%	34.04%
Average Crane Queue Length - Mins	0.02	0
Average Crane Waiting Time - Mins	0.08	0

4.3.3 Simulation Analysis of SW1 Project - Phase Two

City of Edmonton had to change the scope of the work due to a request made by the land developers who co-funded the project. Hence, SW1 tunnel comprises construction of a 2.3-meter diameter (finished diameter with pre-cast concrete segment liners) and 2400-meter long tunnel instead of 2.9-meter diameter 1600-meter tunnel (Er, et al, 1999). The new scope handles the same underground sanitary sewer storage as the original scope. Since the tunnel template was useful in determining certain requirements of the original scope of work, additional modeling features were added to enhance the tunnel template.

(1) Option1 – Continuous Tunneling: Tunnel excavation for 2400 meters from the main shaft, located at the east end of the tunnel, to the removal shaft at the west end.

(2) Option 2 – Two Stage Tunneling: Tunnel excavation commences from the main center-working shaft. In the first phase, 1100 meters of tunnel are excavated towards the east side. The TBM is then removed from the east removal shaft and reset in the main center shaft, and begins excavating the west side of the tunnel for 1300 meters.

(3) Option 3 – Intermediate Undercut: Since Option 1 showed that the tunnel productivity drops after about 800-1000 meters as a result of the TBM waiting for the trains, two alternate ideas were considered to reduce the train travel time: shifting the entire dirt removal to an intermediate location (1100 meters), and utilizing a third train and install a traffic switch at 1100 m from the main shaft. Re-establishing the dirt removal system to the intermediate location after 1100 meters of tunnel was the option adopted for modeling.

Table 4-4 summarizes the utilization of the main resources, productivity, and the cost per meter for all three options. Figure 4-5 shows average tunnel advance rates for options 1 and 3. The simulation analysis showed that higher productivity could be obtained from both options 2 and 3. The tunnel production rate is gradually reduced in longer tunnels when the TBM must wait for the train. The analysis demonstrated that the shifting of the dirt removal process to the intermediate undercut would solve this problem. The excavation of the tunnel from the intermediate undercut for both directions was found to be an adequate solution as well. However, there are additional costs involved with both options 2 and 3, such as setting up an intermediate shaft and undercut. The City of

Edmonton's Drainage Service, Design and Construction Division decided that a better evaluation could be performed to identify the most feasible and productive method when those additional costs can be established.

Table 4-4: Simulation results of Phase 2 of SW1 Project

Option	TBM Utilization	Hoist Utilization	Avg. Productivity (m/8 hour shift)	Duration (8 hour shifts)	Cost ($/m)
1	70.52	34.16	9.12	264	$ 1,110.94
2	81.97	39.73	10.60	228	$ 1,055.59
3	82.08	39.78	10.64	226	$ 1,054.05

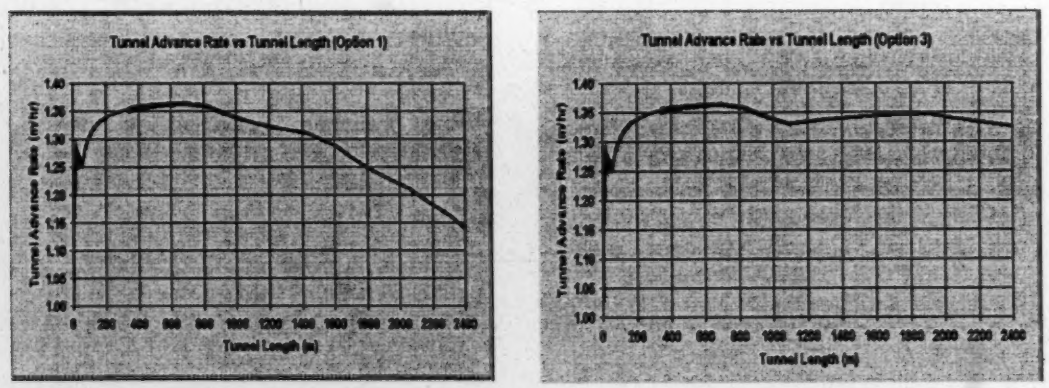

Tunnel Advance Rate vs Tunnel Length (Option 1)
Tunnel Advance Rate (m/hr)
Tunnel Length (m)
Tunnel Advance Rate vs Tunnel Length (Option 3)
Tunnel Advance Rate (m/hr)
Tunnel Length (m)

Figure 4-5: Tunnel Advance Rates (Option 1 – Left) and Option 3 (Right) in Stage 2 Analysis of SW1 Project

4.3.4 Simulation Analysis of SW1 Project - Phase Three

The length of the tunnel has been increased to 2500 meters because of site constraints and land development requirement. The management at City of Edmonton conducted a detailed risk management workshop using the structured risk analysis process explained by AbouRizk (2000). The risk analysis resulted in the recommendation of using two-way tunneling from the main center shaft in both directions with two TBMs as the alternative with the least risk, which became Option 4 (Figure 4-6). Stage 2 also shows very small utilization (below 40%) of the hoist for all options. If one hoist is used for both directions, the tunnel cost could be decreased while maintaining a better-optimized system. The following are the brief descriptions of alternatives considered for final analysis of the SW1 project using the tunnel template (Er et al. 2000). The tunnel template had to be embellished to analyze for some of the alternatives.

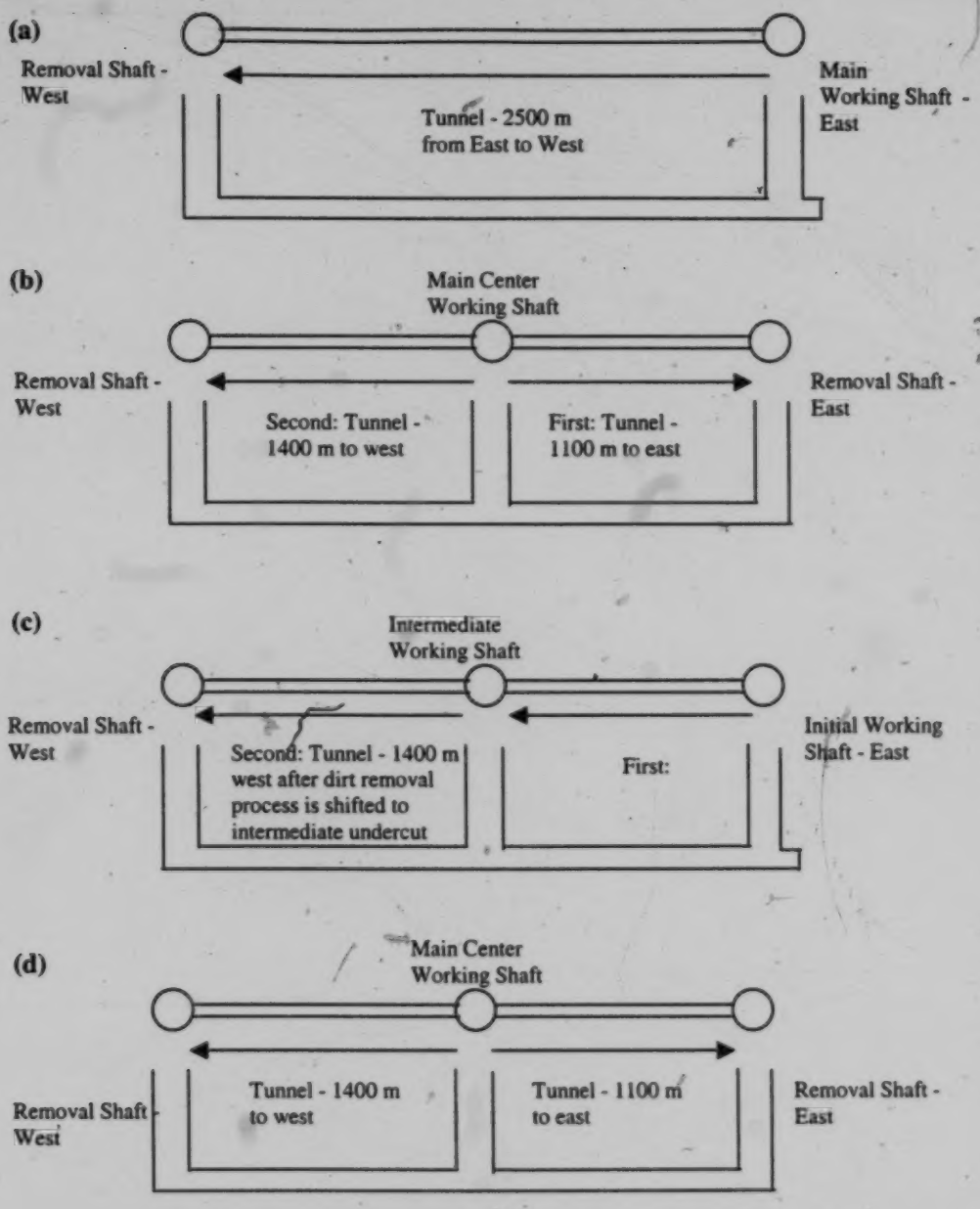

(a)
Removal Shaft - West
Tunnel - 2500 m from East to West
Main Working Shaft - East
(b)
Main Center Working Shaft
Removal Shaft - West
Second: Tunnel - 1400 m to west
First: Tunnel - 1100 m to east
Removal Shaft - East
(c)
Intermediate Working Shaft
Removal Shaft - West
Second: Tunnel - 1400 m west after dirt removal process is shifted to intermediate undercut
First:
Initial Working Shaft - East
(d)
Main Center Working Shaft
Removal Shaft - West
Tunnel - 1400 m to west
Tunnel - 1100 m to east
Removal Shaft - East

Figure 4-6: Plan and elevation layouts for all options of the SW1 Project: (a) Option 1- continuous tunneling from east to west, (b) Option 2 - two-stage tunneling using one TBM, (c) Option 3 - intermediate undercut at 1100 meters from tunnel face, (d) Option 4 - two-way tunneling using two TBM

(1) Option 1 (Model1): Tunnel excavation for 2500 meters from the main shaft, located at the east end ofthe tunnel (Parsons Road), to the removal shaft (111 street) at the west end (Same as Alternative 1 described in Section 4.3.1).

(2) Option 2 (Model 2): Tunnel excavation commences from the main center-working shaft at 104 Street. In the first phase, 1100 meters of tunnel are excavated towards the east side (Parsons Road). The TBM is then removed from the east removal shaft and reset in the main center shaft, and begins excavating the west side (111 Street) of the tunnel for 1400 meters (same as alternate 4 described in Section 4.3.1).

(3) Option 3 (Model 3): One-way tunneling of 2500 meters from east to west (option 1 in Phase 2) showed that tunnel productivity drops after about 1 km due to the TBM waiting for the trains. Then two alternative ideas were considered to reduce the train travel time:

- utilizing a third train and installing a traffic switch at 1100 m from the main shaft (alternate 2 described in Section 4.3.1) or
- shifting the entire dirt removal to an intermediate location at 104 street (1100 m) which is the alternate 3 described in Section 4.3.1.

Re-establishing the dirt removal system to the intermediate location after 1100 meters of tunnel was the option adopted for modeling.

(4) Option 4 (Model 4): The management at City of Edmonton conducted a detailed risk management workshop. The risk analysis resulted in the recommendation of using two-way tunneling from the main center shaft in both directions with two TBMs as the alternative with the least risk. In this alternative, the tunnel's main working shaft is located at 104 Street. 1400 meters of tunnel are excavated towards the west side

(111 Street) and 1100 meters of tunnel is excavated to the east side (Parsons Road). This is the fifth alternative considered by City of Edmonton.

City of Edmonton felt that the tunnel cost could be reduced while maintaining a better-optimized system by increasing the hoist utilization via two-way tunneling. Hence, the tunnel template has been embellished to model a two-way tunnel construction operation. Two-way tunneling is one of the major embellishments to the tunnel template. The following are the modeling algorithms. In this option, excavation is performed for two opposite directions using two tunnel-boring machines, 1400 meters to the west and 1100 meters to the east from the main center shaft.

(1) The east side does not start until the west side reaches a certain distance (about 150-200 meters – user defined input) to avoid congestion.

(2) There will be one track laid to each face of the tunnel. The tracks in each tunnel direction are joined by two parallel tracks in the undercut where dirt removal to the surface takes place.

(3) Two trains are assigned for each side, and the assigned trains can only serve the assigned side. However, any of the trains can park on either one of the tracks.

(4) Each time a train reaches the undercut with dirt (from *west* side for example), the following situations could occur (the same scenario applies for the east side as well):

   a) Both *west* and *east* assigned trains are waiting at the undercut after unloading dirt. When the train with loaded muck cars arrives at the undercut, the emptied train for the east tunnel temporarily backs to the east tunnel. This allows the train with loaded muck cars to move into the undercut area to be ready for dirt removal

operation. As soon as the fully loaded west train is cleared from the track in west tunnel, the emptied train for the west that was waiting at the undercut, immediately leaves for the west tunnel face. The emptied east train now moves forward to the track vacated by the emptied west train in the undercut. This process is reversed when a train from the east tunnel arrives with a full load of dirt.

b) When the train from the west tunnel arrives at the undercut with a fully loaded muck cars while the muck cars from the east train are being unloaded, the dirt disposal from the east train will discontinue temporarily. This east train will temporarily backs to the east tunnel to allow the fully loaded west train to move into the undercut track. The west train with emptied muck cars immediately leaves for the west tunnel face. The partially unloaded east train moves forward to the track vacated by the emptied west train in the undercut and recommences the dirt removal process. The dirt removal for the fully loaded west train will start immediately after the dirt is unloaded from the east train. This process is reversed when a train from the east tunnel arrives with a full load of dirt.

c) The *east* train is waiting at the undercut (after unloading dirt or with dirt waiting for the crane) while the *west* train is unloading the dirt. If the second train from the west reaches the undercut with a full load of dirt, it waits until the first *west* train finishes unloading. Once the dirt removal is completed, it will choose the method (a) explained above. This process is reversed when a train from the east tunnel arrives with a full load of dirt.

Table 4-5: Comparison of all options in Stage 3 Simulation Analysis

Description	Option 1	Option 2	Option 3	Option 4
Basic Tunnel Cost (per Meter)	$ 1,238.25	$ 1,149.63	$ 1,145.05	$ 1,109.13
Basic Tunnel Cost	$ 3,095,624.16	$ 2,874,073.44	$ 2,862,613.92	$ 2,772,813.60
Other Fixed Costs	$ 1,392,500.00	$ 1,820,000.00	$ 2,087,500.00	$ 1,755,000.00
Mobilization/ Demobilization	$ 150,000.00	$ 225,000.00	$ 250,000.00	$ 200,000.00
Main Shaft	$ 560,000.00	$ 560,000.00	$ 560,000.00	$ 560,000.00
Main Undercut	$ 375,000.00	$ 375,000.00	$ 375,000.00	$ 585,000.00
Tail Tunnel	$ 50,000.00	$ -	$ 50,000.00	$ -
Removal Shaft/s	$ 187,500.00	$ 375,000.00	$ 187,500.00	$ 375,000.00
Future Connection	$ 35,000.00	$ 35,000.00	$ 35,000.00	$ 35,000.00
Service Shaft	$ 35,000.00	$ -	$ -	$ -
Intermediate Shaft	$ -	$ -	$ 400,000.00	$ -
Enlarge Undercut	$ -	$ 250,000.00	$ 230,000.00	$ -
Operational Cost ($ 700/day)	$ 244,300.00	$ 203,700.00	$ 201,600.00	$ 121,800.00
TOTAL	$ 4,732,424.16	$ 4,897,773.44	$ 5,151,713.92	$ 4,649,613.60
Cost ($/Meter)	$ 1,892.97	$ 1,959.11	$ 2,060.69	$ 1,859.85
Duration (Shifts)	349	291	288	174
Productivity (m/Shift)	7.20	8.60	8.72	8.80
TBM Utilization	67.00%	80.70%	81.30%	75.30%
Hoist Utilization	29.70%	35.00%	35.38%	70.20%

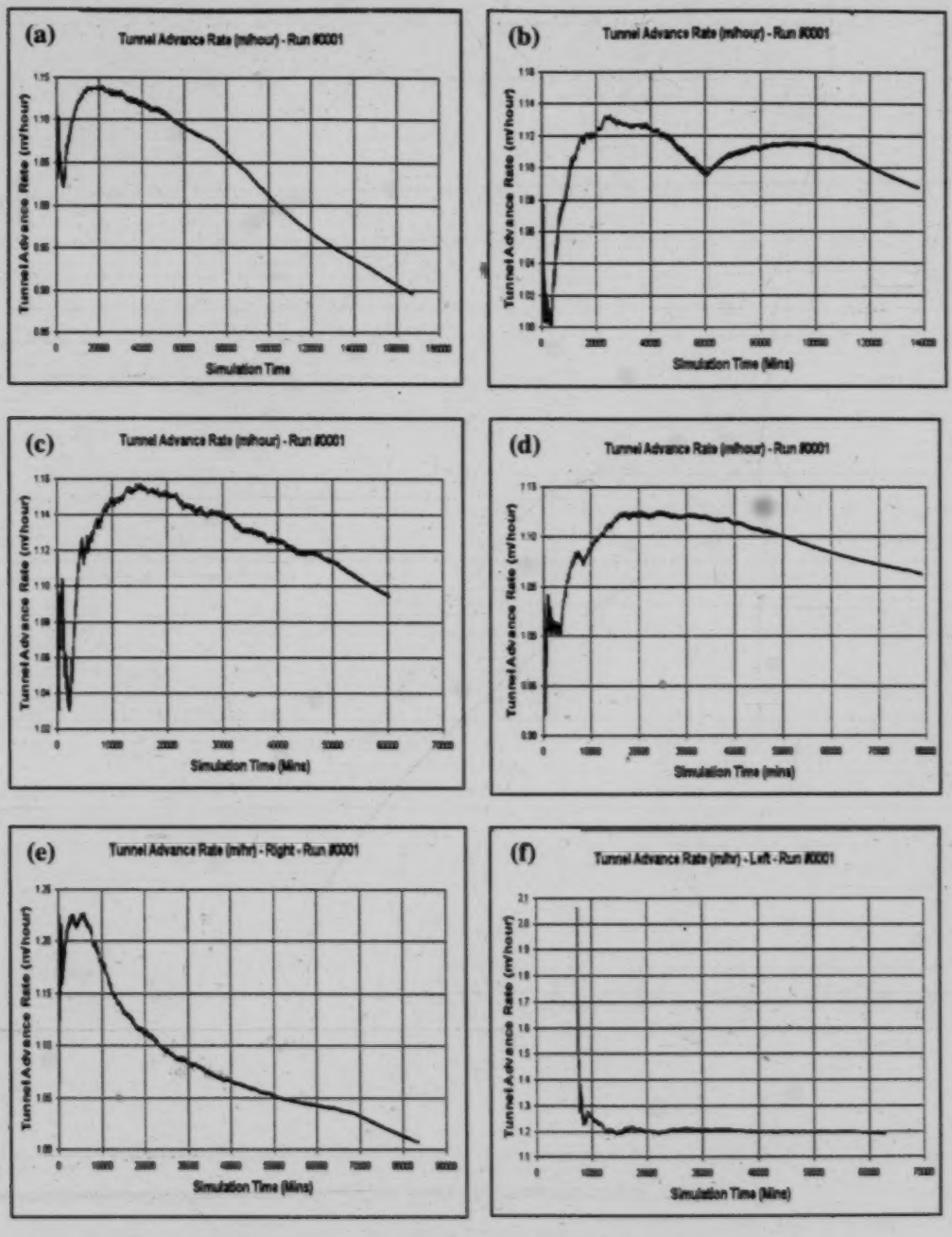


Figure. 4.7. Tunnel advance rates for all options of the SW1 tunnel: (a) Option 1, (b) Option 3, (c) Option 2 – east, (d) Option 2 – west, (e) Option 4 – west, (f) Option 4 – east.

4.3.5 Observations from SW1 Simulation Analysis

Table 4-5 summarizes the basic cost, other costs, resource utilization, productivity, and duration for all options. The tunnel advance rates for all options are in shown in Figure 4-7. The tunnel production rate gradually reduced in this project as shown in Option 1 of Figure 4-7. TBM utilization of Option 1 is comparatively less as illustrated in Table 4-5. The shift of the dirt removal process to the intermediate undercut would solve the problem of prolonged waiting of the TBM for trains. Hence, the excavation of the tunnel from intermediate undercut for both directions is a good alternate solution. However, there are additional costs involved with both options 2 and 3. The main shaft and future connection costs are equal for all options. The mobilization and demobilization are comparatively high in options 2, 3 and 4, compared to that of option 1. Tail tunnel costs are only incurred in options 1 and 3. Option 4 has high undercut costs to support additional tracks for train movement and to set-up tunnel boring machines for both sides. Additional removal shaft costs are incurred in option 2 and 4 due to two-way tunneling. Since option 1 has a continuous 2500 meters of tunnel excavation, at least one service shaft is required. Option 3 incurs additional expenses for an intermediate shaft. The cost of enlarging the undercut is applicable for two options: to operate two–way tunneling (option 2) and to relocate the dirt removal process (option 3).

When comparing the total costs, option 1 is the most favourable option if operational cost (based on duration) is not considered. However, the structured risk analysis process (AbouRizk 2000) results showed that option 1 is the most risky option. Since option 1 requires the excavation of 2500 meters from the east end to the west end, they suspected

that the TBM may not be able to efficiently work for that length without the support of many service shafts, which may incur extra expenditures. Overall, the best results were obtained from option 4. It provides the lowest operating cost and the shortest duration. Since two tunnel boring machines are operated at both directions, the target productivity could be maintained. Option 4 also shows that the hoist utilization is about 70%, which is an acceptable utilization percentage compared to the hoist utilization of the other three options, which are below 35%. The TBM utilization is about 75% in option 4. The major bottleneck in option 4 is the movement of the trains at the undercut. The use of effective communication among the train drivers, the laborers at the undercut, and the hoist operator could avoid this bottleneck.

Tunnel simulation outputs such as tunnel advance rate, resource utilization, and wait times helped to evaluate alternative options for a proposed tunnel project. Simulation analysis further justified the recommendations made using the structured risk analysis process (AbouRizk 2000) to allow City of Edmonton management to consider better options during the project planning stages. The engineering and management staff has suggested new ideas, options and alternatives for resources, and operations to modify the tunnel template. As a result, the tunnel simulation template has been very useful in decision-making for the South Edmonton Sanitary Sewer tunnel.

4.4 Application to Bidding Analysis for the Calgary Trail Interchange Tunnel (CTIT) Project

The tunnel template was used to determine the optimum use and number of trains and muck cars at the bidding stage of the CTIT project. City of Edmonton competed with 4 other bidders and won the contract. The scope of the tunnel is only 510 meters, of which 390 is lined with pre-cast segments while the remaining 120 meters, located just below the Calgary Trail highway, is lined with rib and lagging.

During the bidding stage, City of Edmonton engineers evaluated the productivity of the tunnel project using the template to changing the number of trains. If two trains are used, the undercut area required an additional expenditure of about $125,000. Hence, the template was used to compare the productivity of using 1 or 2 trains with a constant number of dirt muck cars for each train. The simulation results showed that using one train for this short tunnel is more productive than using 2 trains, and saves almost $100,000 as it does not require additional maneuvering space to enlarge the undercut. City of Edmonton not only had an efficient method of evaluating alternate schemes, but also had the chance to improve the cost and duration due to the analysis made using the tunnel template.

This tunnel project was completed in mid of 2000, with a saving of approximately $100,000 from the tunnel excavation and lining portion (Fraser and Weatherly 2000). The expected productivity of the tunnel simulation was almost achieved in the actual construction, as the tunnel project did not have any reportable problems including soil

conditions during tunneling. A productivity analysis of using the Method Productivity and Delay Model (MPDM) can be found in AbouRizk et al (2000).

4.5 Uncertainty of soil conditions causing inaccuracies in the prediction of Productivity in tunnel construction

The preliminary version of the template was used to predict the construction of Mill Creek Interconnection Redemption Project in Edmonton. The Mill Creek tunnel project comprises the construction of a 277 meter tunnel using close faced Tunnel Boring Machine (TBM) in Sandstone. The finished diameter of the tunnel in 2.3 meter diameter and lined with pre-cast concrete segments. The input data parameters were obtained after consultation with the tunneling supervisor and tunnel crewmembers to apply the scenario of Mill Creek tunnel to simulation template. Several statistical distributions were adopted for the relevant tasks to predict the tunnel production of the Mill Creek Project. Figure 4-8 shows tunnel production of the Mill Creek tunnel predicted from the tunnel template.

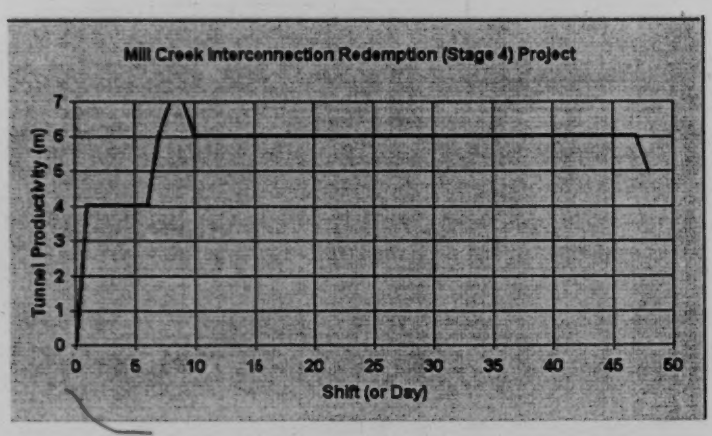


Figure 4-8: Predicted Tunnel Production for Mill Creek Tunnel

The Mill Creek tunnel project commenced in mid July 1999. The progress of the tunnel project was badly affected by unforeseen and unpredictable events, which occurred during tunneling. Based on the geological site investigation, the engineers had lowered the invert of the tunnel alignment assuming that the soil at the new alignment is as same as the alignment shown in the boreholes. However, the soil properties at the new alignment were different and worse than what was shown in the boreholes. As a result of the worse soil conditions, the TBM could not proceed at its normal efficiency during the first 40 days of work. Several layers of sandstone were encountered. Jack hammering and drilling had to be employed to break the sandstone layers before TBM proceeds in the correct direction. Figure 4-9 shows the actual production of the tunnel project.

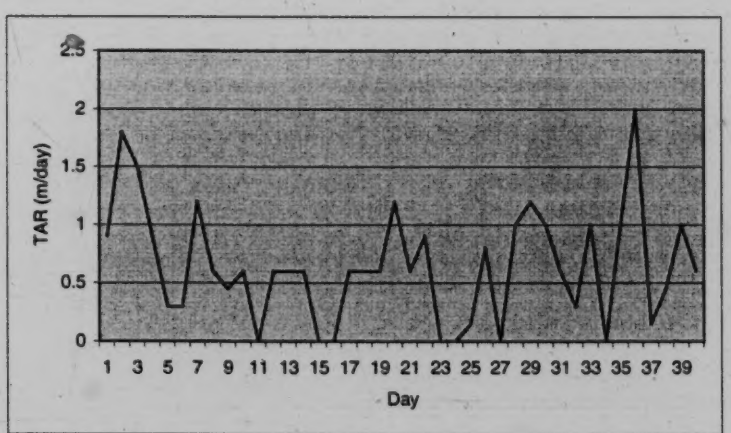


Figure 4-9: Actual Tunnel Production for Mill Creek Tunnel

The following are the main problems encountered at the site and the consequences that led to poor productivity.

a) The sandstone layer was difficult to bore with the TBM and hence, drilling and/or jack hammering had to be used to break the sandstone layer.

b) Several thick layers of sand stone were found at some stages where Jet-cutting (high-pressure water) had to be used.

c) TBM used to break the edges of the perimeter after drilling or jack hammering had broken the sandstone layers. Only a handful of days, the TBM managed to excavate without any difficulty.

d) Unstable ground conditions forced the workers to stabilize the front of the tunnel face using rib and lagging method.

e) Breakdown of the hydraulic mechanism of the TBM and the work was lost for one day.

f) Inability to find sufficient amount of workers to bore the tunnel face.

The simulation results of the Mill Creek Tunnel Project showed that the uncertainty factors could not be predicted using this version of the simulation template. In this particular project, the adverse soil conditions along with few other factors have caused a very low productivity of the tunnel progress.

Figure 4-10 illustrates the macro-level relationship chart for tunnel simulation to identify the uncertainty. One of the critical factors, the soil conditions, has been selected as the primary variable for modeling and implemented within simulation environment. The addition of the enhancements by predicting the soil conditions will help consultants and contractors to develop more realistic approaches during both project planning and the construction phases to meet the challenges they will face as construction progresses.

4.6 Conclusions

The application of simulation to tunnel construction was a new experience for the City of Edmonton, although they have been excavating tunnels for the last fifty years. A Special purpose simulation template developed with Simphony for tunnel construction enabled the City of Edmonton to evaluate various tunneling options expeditiously, primarily allowing the engineers to test the validity of their construction planning strategies.

The productivity of tunneling depends on various factors, such as penetration rate for boring, liner installation time, train speed, length of tunnel, and the hoisting times. The testing of the tunnel template as stated in Chapter 3 also helped to identify the critical factors that affect the tunnel productivity. The analysis of the results shows that simulation can be very useful in predicting the productivity of tunneling and evaluating the cost and duration of various options. The cost-planning module in the tunnel template is a very useful tool for decision-making and evaluating the feasibility of the tunnel construction methods. It also gives estimators and planners the opportunity to produce a more realistic project schedule and estimate. The template can also be used during construction as a control tool. The collection of data in the same project can be applied to generate the productivity for the rest of the project. Hence, this tool is not only used as a planning tool but also as a controlling tool during construction. This enables the planners and engineers to observe productivity and resource utilization levels and conduct additional testing to improve the efficiency of the system using the available resources during construction. The successful implementation of simulation for decision making of

actual construction work is due to interactive collaborative research work between academia and industry, joint team effort, customization to suit industry's requirement, and the flexibility of the computer technology used to develop the simulation tool.

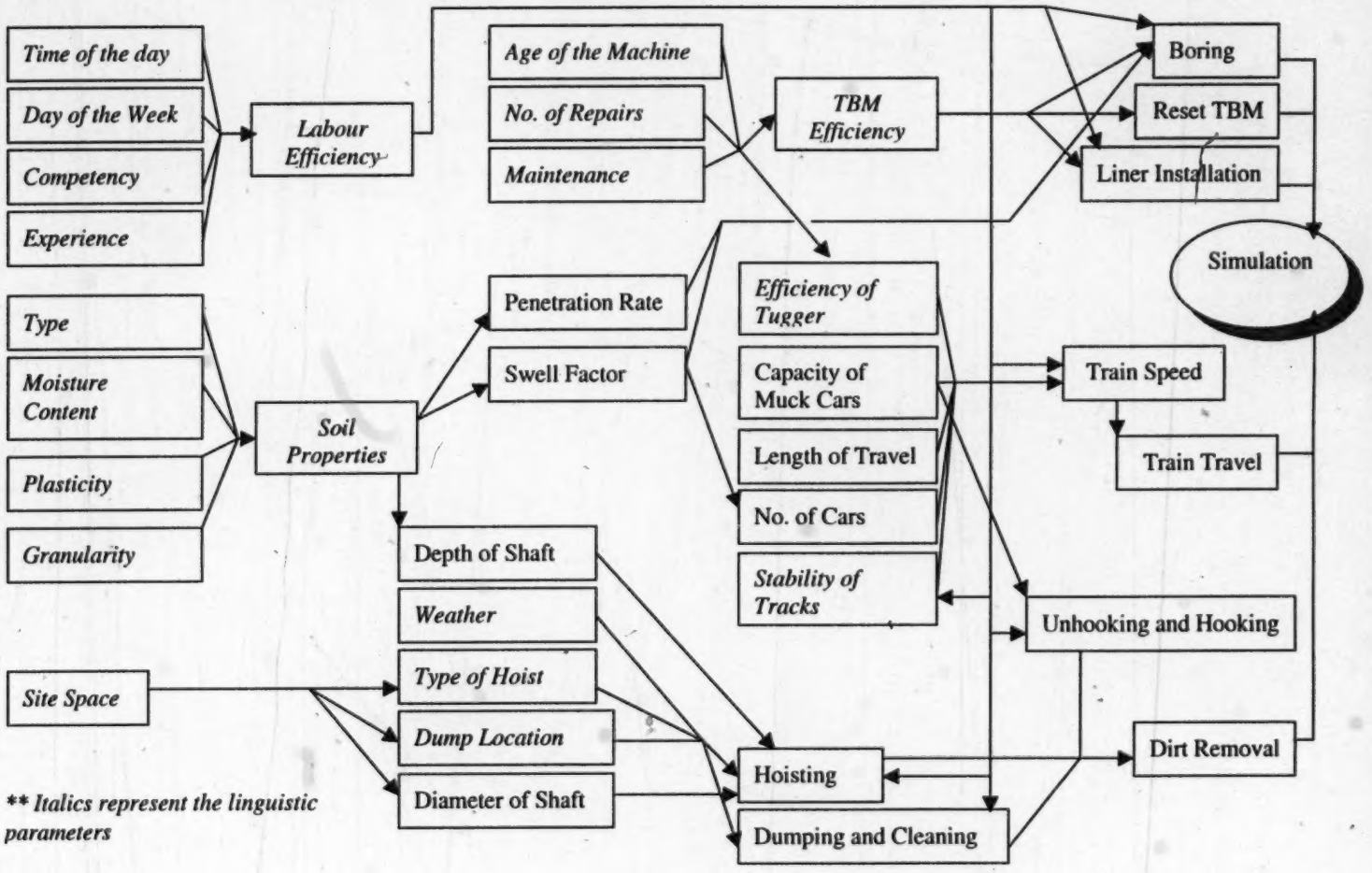


Figure 4-10: Macro-level Relationship of the Variables impacting the Tunnel Construction Productivity

Chapter 5: Characterization and Prediction of Soils along the Tunnel Path

5.1 Introduction

Geologic information is difficult to quantify because observational data are often imprecise and incomplete. Soil characterization starts with the choice of an appropriate geologic model, based on the geologic observation of the area under consideration. Given a geologic model, probability methods can be used to evaluate available information and estimate the uncertainties in geology and various elements of the site characterization (Wu at al. 1991).

In tunnel construction, vertical boreholes only show the soil types that are present in the borehole locations. The soil profiles between the boreholes are uncertain. Practitioners make assumptions about the soil profiles for construction purposes. Chapter 4 showed a case study of a tunnel that had been affected by adverse soil conditions. There are various factors in predicting soil conditions in an area. The availability of a particular soil type, start and end elevations (Appendix "A" provides the meaning of various terminology used throughout this chapter) of the soil layers, thickness of the soil layers, and distribution of the soil layers between the known boreholes are some of the major factors that affect tunnel construction productivity.

The proposed method addresses these major factors using an analytical approach. The construction engineers or managers could use the analysis presented in the chapter to strengthen the geological data obtained for the project. The geotechnical engineer or

geologist view of how to characterize the soil types is not the purpose of this analysis. The geologic prediction and the related analysis are based on the works of Allouche and Ruwanpura (2001) that define analytical methodologies for tunnel construction operations. The approach is as follows:

1. Identify and characterize the main soil types that exist in a given area.
2. Divide the area into several clusters based on the soil types in the boreholes. A concept of family (see Appendix "A") has been introduced for the analysis.
3. Predict the probability of having a particular soil type in the area.
4. Predict the possible combinations of soil families in the area and their distribution. This enables one to identify the existence of both continuous and non-continuous soil types (see Appendix "A") along the tunnel direction.

Section 5.2 presents an overview of the Edmonton geology that was used as the base data throughout this chapter for the soil prediction analysis although the prediction methodology is not confined to Edmonton geology. The same principles or concepts proposed in this chapter could be applied to any other area. Section 5.3 provides an overview of the soil families. Section 5.4 discusses the soil clusters used in this analysis. The prediction of the probability of the existence of the soils is detailed in Section 5.5. Section 5.6 presents the methodology to predict the soil families along the tunnel path. Section 5.7 then shows applications of the prediction of the soil families for two tunnel construction projects. Section 5.8 explains how the prediction of soil families could reduce the uncertainty between the boreholes to determine the transitions of soils along

the tunnel. The limitations of the borehole data are discussed in Section 5.9. The conclusions are given in Section 5.10.

5.2 Edmonton Geology

Geology of Edmonton was studied and used as the base data for analysis, prediction, and illustration purposes. The following is a brief explanation of the geologic terminology used in the drill log and the stratigraphic section descriptions (McPherson and Kathal 1972) for the Edmonton area.

1. Bedrock: The Edmonton Formation, composed of interbedded bentonitic shales and sandstone with numerous coal seams, underlies most of the area.
2. Bedrock (ice-shoved): Block of bedrock material underlain by glacial deposits is common in the area. They have been moved by glacier ice and are referred to as ice-shoved bedrock.
3. Disturbed Saskatchewan gravels and sands: Saskatchewan gravels and sands that have been disturbed by glacier ice.
4. Saskatchewan gravels and sands: Quartzose sediments varying from fine sand to coarse gravel, fluviatile in origin and deposited prior to glaciation in the area.
5. Glacial till: Unsorted unstratified sediment deposited by a glacier, composed of clay, silt, and sand with pebbles and boulders; lenses of outwash sand, gravel, or disturbed bedrock are common.
6. Glacial sand and gravel: Mainly sand and gravel deposited by glacial melt water.
7. Lacustro-till: Glaciolacustrine sediments melted with pebbles and till-like layers deposited by mudflows, ice rafting, or both, into a glacial lake.

8. Glaciolacustrine deposits: Bedded sands, silts and clays deposited in a large preglacial lake called Glacial Lake Edmonton.
9. Glaciolacustrine deposits: Mainly fine sand and silt deposited in a large delta in Glacial Lake Edmonton.
10. Aeolian deposits: Sand, medium- to fine-grained in sheet or dune form, thin to 50 feet thick
11. Alluvium: Recent river terrace and floodplain deposits consisting of clay, silt, and gravel

However, these soil conditions can be divided into four (4) major categories for tunneling purposes, according to Montgomery and Eisenstein (1995):

1. Bedrock (type 1 and 2 above),
2. Glacial Till (mainly type 5 above),
3. Saskatchewan sands and gravels (type 3, and 4 above) and sand lenses (type 6 above),
4. Lake Edmonton Clay (type 7, 8, 9, 10, and 11 above).

The Edmonton geological information was collected from two different sources. The main source was the borehole drilling data presented in both Kathal and McPherson (1975) and McPherson and Kathal (1972) through the Research Council of Alberta (ARC). The second source was the borehole data collected from past City of Edmonton sewer and tunnel construction projects. According to ARC data, all the boreholes were drilled on a 1-mile grid system as indicated in Figure 5-1. The total area is approximately 324 square miles (18 miles x 18 miles). The Y-axis is represented by EW (East West) and the X-Axis is represented by NS (North South). The X-axis has values from NS9 to

NS18 to divide the axis approximately by 2 mile intervals as shown in Figure 5.1. Similarly, the Y-axis has values from EW1 to EW 9 to divide the axis approximately by 2 mile intervals as shown in Figure 5.1. The major points along an axis are further divided into two sections (1 mile each) for both axes. For example, EW1.5 is approximately the mid point between EW1 and EW2. Generally, at least one borehole data summary is presented for each intersection of EW and NS axes. For example, there is one borehole on the intersection of EW1.5 and NS13.5 which is shown Figure 5.1. However, there is additional borehole information on certain axes. Figure 5-2 shows part of the cross-section of the soil types in NS12 axis. The numbers in Figure 5-2 indicate the soil descriptions explained above.

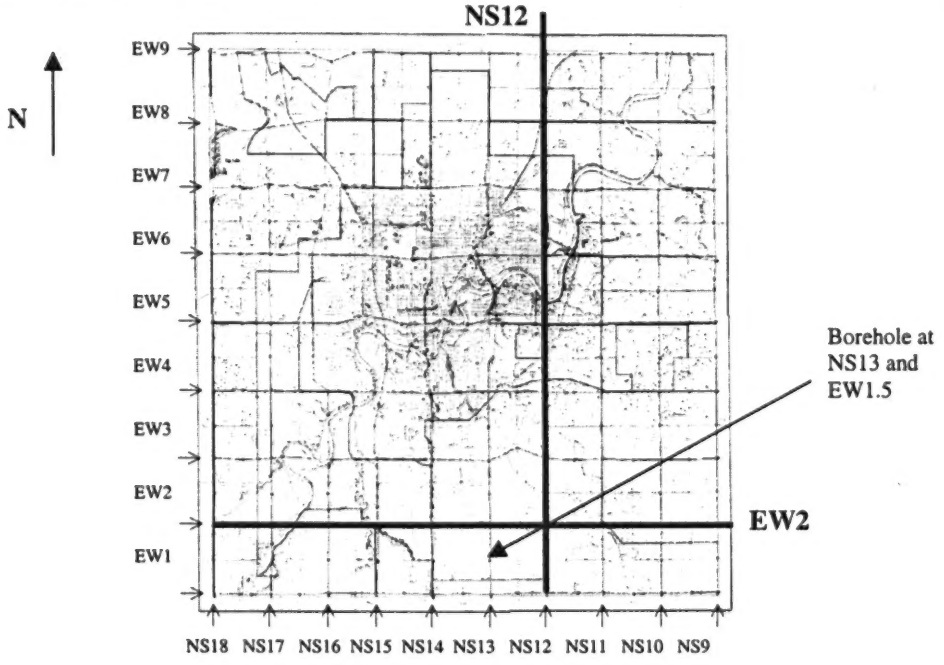


Figure 5-1: Edmonton Borehole Map showing the cross-section axes (Kathal and McPherson 1975)

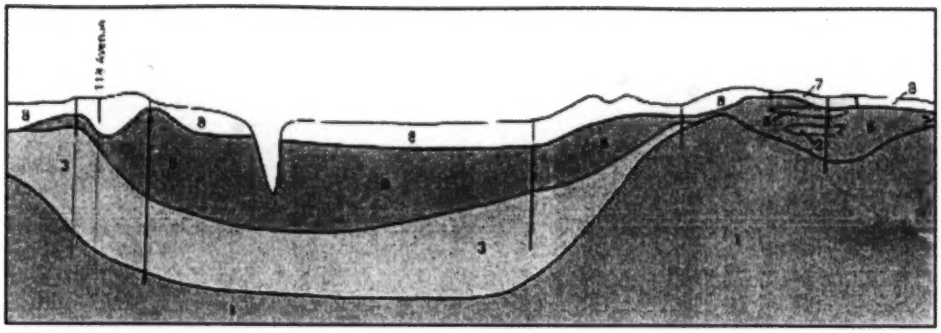


Figure 5-2: Part of the Geological cross-section in the Edmonton Area - North, South 12 Axis (Kathal and McPherson 1975)

Borehole data collected from City of Edmonton based on the previous construction project contains details of 226 boreholes in the South East Edmonton area (Figure 5-3). The depth of the boreholes from the surface varied from 5.8 meters to 43.6 meters. This information does not provide a conclusive image of the soil profiles in the area, as most of the boreholes were not driven up to the Bedrock layer, which is the bottommost layer in the Edmonton area.

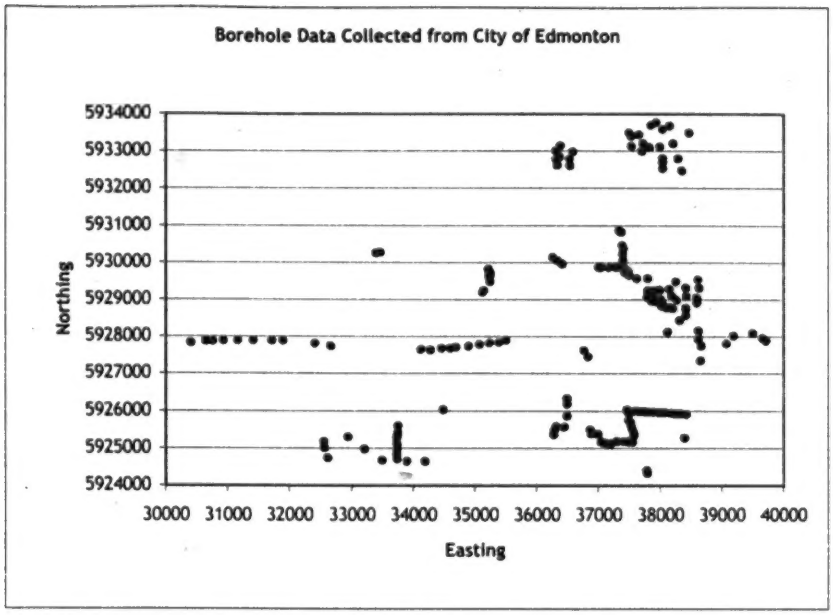


Figure 5-3: Borehole Locations from Previous City of Edmonton Projects in South East Edmonton (not to scale)

The thickness (refer Appendix "A") of all soil types according to the ARC data are in Table 5-1. However, the thicknesses of Bedrock1 in Table 5-1 do not provide an accurate picture. All borehole data was limited to a minimum depth of 2000 feet (609.6 meters), although Bedrock1 layer extends below the 609.6-meter elevation. According to Montgomery and Eisenstein (1995), the BedRock (type 1 and 2) formation varies from 140 to 190 meters, Saskatchewan sands and gravels (type 3) vary from 4 to 20 meters, and sand lenses (type 6) vary from 100 mm to over 50 meters. However, the data obtained from ARC does not comply with the approximate thicknesses indicated by Montgomery and Eisenstein (1995).

Table 5-1: Minimum and Maximum Thicknesses of All Soil Types - ARC Data

Soil Number	Soil Type	Minimum Thicknesses (m)	Maximum Thicknesses (m)
1	Bedrock1	3.05	149.35
2	Bedrock2	1.22	32.00
3	Saskatchewan Gravel Sand1	0.61	48.16
4	Saskatchewan Gravel Sand2	3.05	15.24
5	Glacial Till	0.61	50.29
6	Glacial Sand Gravel	0.61	25.91
7	Lacustro Till	0.61	8.23
8	Glacial Deposit1	0.61	35.97
9	Glacial Deposit2	0.30	25.60
10	Aeolian	7.01	7.01
11	Alluvium	3.05	9.45

5.2.1 General Observations

It is assumed that the boreholes presented by ARC are representative of the area of Edmonton. The geological cross-sections in ARC data can be used to identify the various characteristics that can be seen in the area. The following are the observations made during the conceptual analysis for prediction purposes.

1. Soil Type 1: This soil is also known as Edmonton formation and can be seen throughout the entire area of the Edmonton. It is the bottommost soil layer. Different cross-sections presented by ARC data show that for a general indicator, the elevation shape of bedrock increases from west to east and north to south.
2. Soil Type 2: This soil layer is referred as ice-shoved bedrock. This kind of bedrock is found mainly within glacial clay till (Soil 5). The thickness and distribution of this type of soil varies. Table 5-1 shows that the thickness can vary from a low of 1.22 meters to a high of 32 meters. However, the ARC data shows that 80% of this soil type have thicknesses less than 10 meters
3. Soil Type 3: This disturbed Saskatchewan gravel and sand have been reworked by glacier ice. This soil has been formed at a very early stage. The appearance of soil type 3 at a given location is strongly dependant on the shape of bedrock in that area as this soil is a result of a transformation within the bedrock layer. The thickness of this soil varies from 0.61 to 48 meters with 80% of it less than 20 meters.
4. Soil Type 4: This soil is called Saskatchewan gravel and sand, which is deposited prior to glaciations in the area. This soil is only present in two boreholes within the study area. These locations are located at the intersections of NS9 with EW7.5 and EW3 with NS14.
5. Soil Type 5: Glacial till can be seen almost everywhere in the Edmonton area. It co-exists with many other different soil types. This soil mostly exists above bedrock type 1. When this soil is observed on the surface, the thickness is comparatively higher and mostly deposited directly on the top of Bedrock1 except in a couple of

locations in the North-East of Edmonton. This soil has been deposited in the area at a later stage than soil types 1, 3 and 4.

6. Soil Type 6: Glacial sand and gravel was mainly deposited by glacial melt water. This soil type is mainly found within soil type 5. It is possible to interpret that this soil can be part of the soil type 5 as 40% of the soil contains sand (Bayrock and Hughes 1962). However, it is most likely that this soil immigrated to the areas at a later stage. It is observed also, that when this soil exists within soil type 5 at a certain location, soil type 2 is not very far from that location.
7. Soil Type 7: Lacustro-till was deposited into a glacial lake by mud flows, ice rafting, or both. This soil can be found mainly with soil type 5 and usually exists on the surface. This soil type can be seen side by side with soil type 8 as well as above and below soil 8.
8. Soil Type 8: Glaciolacustrine deposits, bedded sands, silts, and clays deposited in a large pre-glacial lake are called glacial Lake Edmonton. This soil is the most common surficial soil in the area of Edmonton. The thickness varies from 0.6 to 36 meters with over 85% of the thicknesses being less than 10 meters. All other soils, except 11, co-exist with this soil. In few places it is deposited directly on Bedrock 1. Soil 5, 6, 7 and 9 are the other bedding layers for this soil in the area.
9. Soil Type 9: These Glaciolacustrine deposits are mainly comprised of fine sand and silt deposited in a large delta in Glacial Lake Edmonton. This soil was found mainly in the area limited by Central-West and North-West of Edmonton. Generally soil type 5 is the bedding layer. At certain locations, this material was deposited directly on top of soil type 1 or 8. The thickness of this material varies considerably.

10. Soil Type 10: This soil is called Aeolian deposits comprising Sand. It is found only in the southwest area of Edmonton.
11. Soil Type 11: This soil is named Alluvium that comprises river terrace and floodplain deposits consisting of clay, silt and gravel. This soil is deposited on top of Bedrock 1. It is only found in the area of Saskatchewan River. Some kind of coexistence between this soil and soils 3 or 5 can be observed in the area.

5.3 Overview of the Soil Families

A Soil Family is the order of the different soil types that exist vertically at discrete elevations commencing from the surficial soil to the bottommost layer at a given point within an area. There are various soil types in any area; the previous section explained only the various soil types in Edmonton area. The following are some of the major conclusions of the observations of the Edmonton geology.

1. There are different surficial soil types in the area (see Appendix "A" for definition).
2. There are certain soils that exist as the bedding layer to some other soils.
3. There are soils that exist as pockets (see Appendix "A" for definition) within another soil layer.
4. There are some soils that co-exist with other soils.

These conclusions suggest that there could be many variations of soils vertically from the surface to the bedrock layer from one point to another in the area. This means there are several soil families in the area. Some soil families may interact with other soil families, as shown in Figure 5.2. Figure 5.4 is another cross-section from ARC data which shows different soil families.

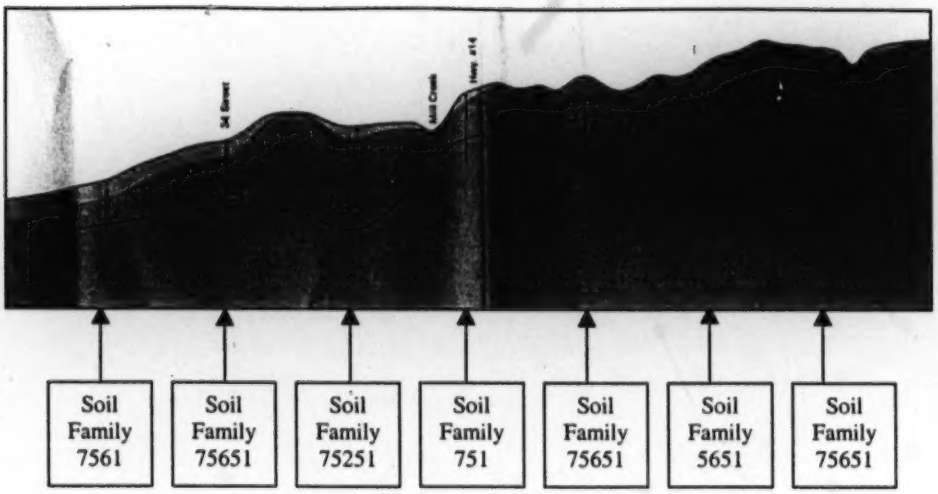


Figure 5.4: Different Soil Families

In Figure 5.4, there are five different families across 7 boreholes. The families are 7561, 75651, 75251, 751 and 5651. According to ARC data, there are 59 families in the Edmonton area. The most common families are given in Table 5-2 and the location of the top four families are graphically illustrated in Figure 5-5. The most common family in the Edmonton area is 851. In 851 family, the soil type 8 (Lake Edmonton) is the surficial soil type, followed by soil type 5 (Glacial Clay Till) and soil type 1 (Bedrock 1). Figure 5.4 shows very clearly that the families co-exist with each other.

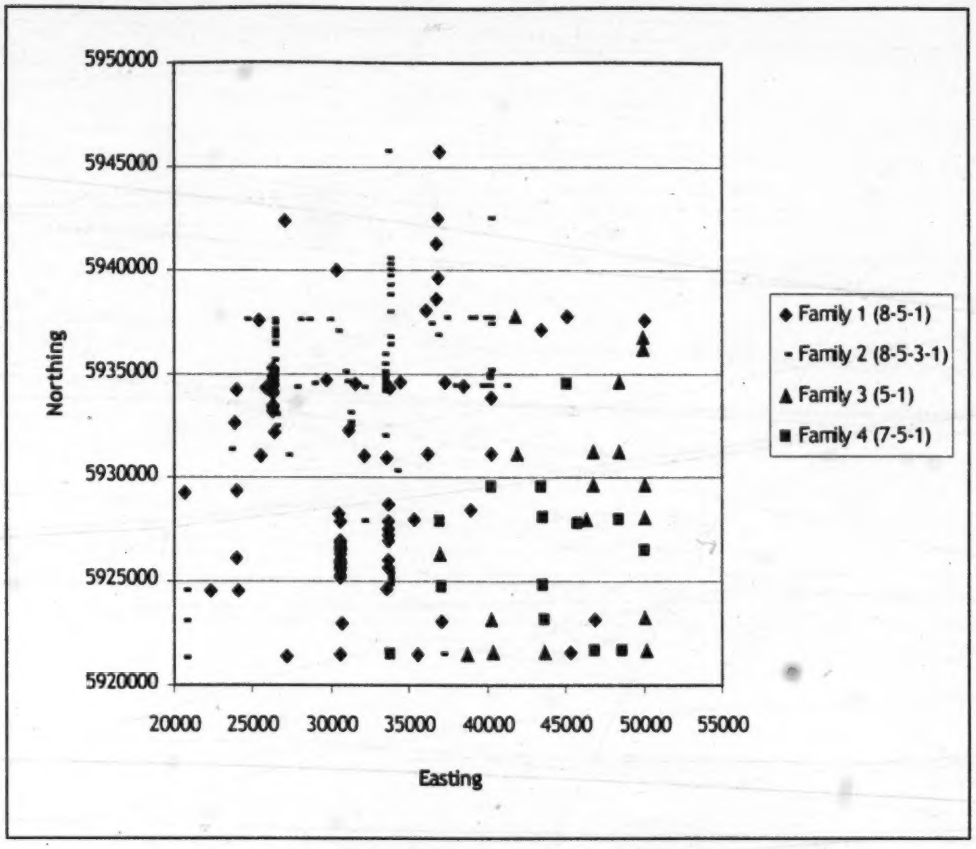


Figure 5-5: Location Map of the Borehole Families

Table 5-2: Most Common Families of Soil in Edmonton Stratigraphy

Total Number of Observations	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6
79	8	5	1			
76	8	5	3	1		
18	5	1				
14	7	5	1			
8	8	5	6	5	1	
6	8	7	5	1		
6	8	5	2	5	1	
5	8	5	6	5	3	1
5	7	5	6	5	1	

5.4 Soil Clusters

Any area can be divided into various clusters (groups) depending on different dependant variables (Issaks and Srivastava 1989). In this study, the area was divided into various clusters based on the surficial soil type irrespective of the other soil types under different surficial soil types. However, there could be several families of soils under one surficial soil. Table 5-4 provides all the families with soil 8 as the surficial soil. Appendix "B" shows all the soil families under different surficial soil types. The probability of existence of a particular soil type is defined in Section 5.5 based on the clusters (CL). In Edmonton area, the surficial soils in the study area include the soil types 5, 6, 7, 8, 9, 10, and 11. It is noted that soil types 1-4 cannot be seen as the surficial material in any of study area.

It can be stated that the area is comprised of different soil clusters based on the surficial soil type. In the study area of edmonton there are seven different clusters. They are cluster 5 (CL_5), cluster 6 (CL_6), cluster 7 (CL_7), cluster 8 (CL_8), cluster 9 (CL_9), cluster 10 (CL_{10}), and cluster 11 (CL_{11}). In the study area of Edmonton (Appendix "B") there are nine different soil families under CL_5, four different soil families under CL_6, 10 different soil families under CL_7, 30 different soil families under CL_8, and one soil family each under CL_9, CL_{10}, and CL_{11}.

Table 5-4: Borehole Details starting from Soil Type 8 (CL8)

Percentage	Total Number	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6	Layer 7	Layer 8	Layer 9
34.80%	79	8	5	1						
33.48%	76	8	5	3	1					
3.96%	9	8	5	6	5	1				
3.08%	7	8	7	5	1					
2.64%	6	8	5	2	5	1				
2.64%	6	8	5	6	5	3	1			
2.20%	5	8	5	6	1					
1.76%	4	8	7	5	3	1				
1.76%	4	8	5	2	3	1				
1.76%	4	8	9	1						
1.76%	4	8	6	5	3	1				
1.32%	3	8	9	5	3	1				
1.32%	3	8	1							
0.44%	1	8	5	4	5	1				
0.44%	1	8	5	6	5	2	3	1		
0.44%	1	8	5	3	5	1				
0.44%	1	8	5	2	5	3	1			
0.44%	1	8	5	3	5	3	1			
0.44%	1	8	5	6	5	2	5	1		
0.44%	1	8	6	1						
0.44%	1	8	9	8	9	5	1			
0.44%	1	8	6	5	1					
0.44%	1	8	7	5	2	5	1			
0.44%	1	8	7	5	6	1				
0.44%	1	8	7	5	6	5	1			
0.44%	1	8	7	6	1					
0.44%	1	8	7	8	5	1				
0.44%	1	8	9	5	1					
0.44%	1	8	9	5	6	5	3	1		
0.44%	1	8	5	6	5	6	5	2	3	1
100.00%	**227**									

5.5 Prediction of the Probability of Existence of Soils

A probability analysis is performed in three stages to determine the likelihood of a particular soil in the tunnel trajectory. The three stages are:

a) Calculation of the probability of existence of different soil clusters.

b) Calculation of the probability of existence of a soil type within different soil clusters.

c) Calculation of the probability of co-existence of a soil type with many other soil types within different soil clusters.

d) Calculation of the probability of finding a soil type at a target point within a particular area with respect to the clusters and the soils that exist in the boreholes.

5.5.1 Probability of existence of the soil clusters

The probability that a particular soil cluster appeared (a particular soil type appeared as the surficial soil) within all boreholes in a given area is calculated using equation 5.1. This probability is referred to as $P_{CLn,}$ where n is the surficial soil type of the cluster. The P_{CL} values provide a good understanding of the extent of the existence of different surficial soil types. The calculated P_{CL} Values of all the surficial soil types are in Table 5-5.

$$P_{CL\ (Soil\ Type\ "A")} = \frac{Number\ of\ Boreholes\ that\ contain\ Soil\ Type\ "A"\ as\ the\ surficial\ soil\ type}{Total\ Number\ of\ Boreholes\ in\ the\ area} \quad \text{.....(5.1)}$$

Table 5-5: P_{CL} Values

Soil Type	Number of Observations	Total Boreholes	P_{CL} Value
5	28	300	0.0933
6	6	300	0.0200
7	35	300	0.1167
8	227	300	0.7567
9	1	300	0.0033
10	1	300	0.0033
11	2	300	0.0067

5.5.2 Probability of Existence of Soils within the Clusters

The proposed method considers the existence of a particular soil type within all clusters to identify the probability of existence of the soil within all clusters in the area. Because of the existence of different clusters in a given area, the probability of a soil type being present is calculated as the summation of probabilities of the existence of a soil type within all the clusters (Equation 5.2). One type of soil could be found under different soil families irrespective of the surficial soil type. For example, soil type 6 can be found when the surficial soil layer is soil 5,6,7,8, or 9 (*i* in Equation 5.2). The examples from Edmonton geology are families of 85651, 8651, 7561, 7651, 651, 5651, 9895651, although the surficial soil layer is soil 5, soil 6, soil 7, soil 8 or soil 9.

$$Probability\ of\ Soil\ Type\ "A"\ (PC_A) = \sum_{i=5}^{n=11} P_{CL\,i} \times \frac{N_i(A)}{T_i} \qquad (5.2)$$

$N_i\,(A)$ is number of times soil type "A" appears at least once within different families under a given *cluster i* and T_i is the total number of different families within a given

cluster i. P_{CLi} is a probability of having a given *cluster i* as calculated in Equation 5.1. Based on Equation 5.2, the probability of soil type 6 within all clusters (PC_6) are calculated and shown in Table 5-6. The calculations of all PC values are shown in Appendix "C." PC values for all the soils are: PC_2 = 0.1999, PC_3= 0.3738, PC_4=0.0356, PC_5=0.8758, PC_6=0.4407, PC_7=0.2932, PC_8=0.8228, PC_9=0.1431, PC_{10}=0.0033, and PC_{11}=0.0067. These PC values indicate that soil type 5 is the mostly common soil type in the area after bedrock 1. These probability values would change according to the existence of various soil types in the area. Although the probability of having soil 8 is 82% within all clusters in the area, this probability value can be either increased or decreased depending on the existence of other soil types and the co-existence of soil 8 with the other soil types in any given area under different clusters.

Table 5-6: Calculation of Probability of a Soil type 6 within all Clusters

Cluster $_i$	P_{CL} Value ($P_{CL\,i}$)	N (6) $_i$	Total (T_i)	N (6) $_i$/T_i	$P_{CL\,i}$×N (6) $_i$/T_i
CL5	0.09333	3	9	0.3333	0.0311
CL6	0.02000	4	4	1	0.02
CL7	0.11667	5	10	0.5	0.0583
CL8	0.75667	13	30	0.4333	0.3279
CL9	0.00333	1	1	1	0.0033
CL10	0.00333	0	1	0	0
CL11	0.00667	0	1	0	0
PC[6]					**0.4407**

5.5.3 Probability of Co-existence of a soil with other soils under different clusters

Because of the co-existence of a soil type with many other soil types in a given area, the probability of the existence of a soil type is measured against the co-existence of that soil

with other soils in the area under different clusters. A particular soil type could co-exist with many other soils. The general observation discussed in Section 5.2.1 and the related soil families discussed in Section 5.3 demonstrated this hypothesis. The probability of existence of a soil therefore depends on its co-existence with other soils irrespective of the soil families and the surficial soil type. It is possible to assume that existence of soil type 3 in the vicinity of a borehole which contains the exclusive family of 8-5-1 as soil 3 co-exists with soils 8,5, and 1. If that assumption is a valid one, the possible families in the neighbourhood could be 8-5-3-1 or 8-5-3-5-1 or 5-8-5-3-1. However, 8-5-6-3-1 cannot be included with the same group because soil 6 is considered as an additional soil.

The equation 5.3 shows the co-existence of Soil type "A" in the neighbourhood of Borehole i which has exclusive soils x,y, and z.

$$NPR[A]_{BH\,i} = \frac{PE(A)_{BH\,i}}{PE(A)_{BH\,i} + QE(A)_{BH\,i}} \qquad (5.3)$$

In Equation 5.3, $PE\,(A)_{BHi}$ is the number of times that soil A exclusively co-exists with other soils (x,y,z) that are in the borehole *BH i* under different families with the surficial soil being x, y, or z (CL_x, CL_y, CL_z). $QE\,(A)_{BHi}$ is the number of times that soils (x,y,z) in Borehole *BH i* exclusively co-exist with other soils (x,y,z) in the borehole *BH i* under different families with the surficial soil being x, y, or z (CL_x, CL_y, CL_z). The following example shows the co-existence of soil type 6 in the neighborhood ($NPR[6]_{BH49}$) of borehole No. 49 that has an exclusive family of 7-5-1. The analysis given below shows that there is a 39% chance of having soil type 6 in the neighbourhood of borehole 49, which has an exclusive family of 751.

Frequency of soil types 7,5,1 (from CL_7)	14	$PE(6)_{BH\,49}$
Frequency of soil types 7,5,1 (from CL_5)	0	
Frequency of soil type 7,5,6,1 (from CL_6)	0	
Frequency of soil type 7,5,6,1 (from CL_7)	9	$QE(6)_{BH\,49}$
Frequency of soil types 7,5,6,1 (from CL_5)	0	
Total Frequency	23	
Probability of existence of Soil Type 6 in the Neighbourhood of 7,5,1	9/23	
$NPR[6]_{BH49}$	**0.3913**	

5.5.4 Predict the Probability of Existence of Soils along the Tunnel Path

The final step of the probability analysis of the soil types is to determine the probability of finding any given soil type at any target point within a particular area. The probability of existence of a particular soil along the tunnel path would vary according to the boreholes, soil families in the boreholes, and the co-existence of this soil with other soils in the area under different clusters. Figure 5-6 and Table 5-7 are used to illustrate the probability analysis explained so far and the future analysis to determine the probability of existence of a soil along the tunnel path. In Figure 5-6, there are several families of soils in the boreholes in the proximity of tunnel, which is 3440 meters long. The families

are 851, 751, 51, 75651, 7561, 85651, and 651 in the respective boreholes. Figure 5-6 depicts the tunnel and the surrounding boreholes. Table 5-8 shows the probability of existence of soil types in the neighbourhood of each borehole using Equation 5.1 to 5.3.

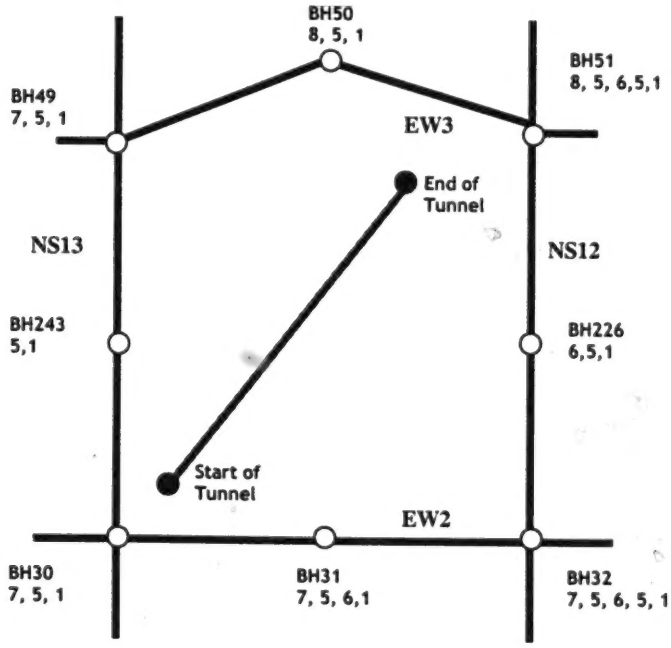


Figure 5-6: Sample Tunnel and the borehole locations (ARC data)

Equation 5.4 given below, calculates the probability of existence of a particular soil type in the tunnel direction with respect to the soil types in the neighbourhood boreholes. In equation 5.4, d_i refers to the distance from Borehole BH_i to the target point in the tunnel direction and n refers to the number of boreholes in the neighbourhood of the tunnel. If the distance from a borehole to a target point is very small, the impact of that borehole's soil types has a higher impact on the target point.

$$NPR(A)\ at\ Target\ T = \sum_{i=1}^{n} \frac{\frac{1}{d_i} \times NPR(A)_{BH\,i}}{\frac{1}{d_i}} \quad \text{.....(5.4)}$$

Table 5-7: Elevations of the Soils in Figure 5-6

BH No	Primary Axis	Cross Axis	Soil No	Start Elevation (m)	End Elevation (m)	Easting (m)	Northing (m)
30	EW2	NS13	7	691.90	686.41	37090	5924750
			5	686.41	676.96		
			1	676.96	609.60		
31	EW2	NS12.5	7	697.69	692.51	38640	5924800
			5	692.51	685.19		
			6	685.19	684.58		
			1	684.58	680.92		
32	EW2	NS12	7	710.18	705.92	40250	5924810
			5	705.92	693.42		
			6	693.42	691.90		
			5	691.90	689.46		
			1	689.46	611.43		
49	EW3	NS13	7	690.98	687.93	36960	5927855
			5	687.93	686.10		
			1	686.10	610.82		
50	EW3	NS12.5	8	683.06	679.40	38960	5928480
			5	679.40	667.51		
			1	667.51	609.90		
51	EW3	NS12	8	701.04	698.60	40535	5928000
			5	698.60	695.55		
			6	695.55	672.39		
			5	672.39	671.47		
			1	671.47	611.12		
226	NS12	EW2.5	6	710.18	701.95	40290	5926410
			5	701.95	688.85		
			1	688.85	557.78		
243	NS13	EW2.5	5	695.25	692.20	36990	5926270
			1	692.20	542.85		

Table 5-8: Probability of the co-existence of a particular soil type in the neighbourhood of the boreholes in Figure 5-6

Borehole No	Family	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	Type 7	Type 8	Type 9	Type 10	Type 11
49	751	1.000	0.222	0.222	0.000	1.000	0.391	1.000	0.391	0.000	0.000	0.000
243	51	1.000	0.000	0.100	0.053	1.000	0.280	0.438	0.816	0.000	0.000	0.000
30	751	1.000	0.222	0.222	0.000	1.000	0.391	1.000	0.391	0.000	0.000	0.000
31	7561	1.000	0.100	0.100	0.000	1.000	1.000	1.000	0.182	0.000	0.000	0.000
32	75651	1.000	0.100	0.100	0.000	1.000	1.000	1.000	0.182	0.000	0.000	0.000
226	651	1.000	0.000	0.125	0.000	1.000	1.000	0.563	0.667	0.000	0.000	0.000
51	85651	1.000	0.067	0.417	0.000	1.000	1.000	0.125	1.000	0.000	0.000	0.000
50	851	1.000	0.070	0.490	0.012	1.000	0.149	0.101	1.000	0.036	0.000	0.000

Figure 5-7 depicts the existence of soil type 6 based on the probability values calculated using Equation 5.4 for the tunnel shown in Figure 5-6. It clearly shows that the probability of existence of soil 6 increases from the start of the tunnel to a peak around 2330 meters from the tunnel starting point and then drops down marginally until the tunnel's end. Although the probability values are greater than the PC_6 value, it is not possible to rule that the soil type 6 is present in the area without a threshold value to accept or reject the existence of soil type 6. The same example provides the following observations. Figure 5-8 provides the small-scale representation of each soil's probability of existence from the start to the end of the tunnel.

1. P_{CL} values of soil types 2, 3, 4, 8, 9, 10, and 11 calculated using Equation 5.2 are greater than the probability of existence in the neighbourhood of the boreholes calculated using Equation 5.4. Therefore, the existences of these soil types are questionable in the tunnel path.
2. The probability of existence values (NPR) for Soil 2 and 7 decrease from the start to the end of the tunnel. NPR values for soils 3, 8 and 9 increase from the start to the

end of the tunnel. NPR values for soil 4 increases to a peak around 1000 meters from the start of the tunnel and then drops towards the tunnel's end.

These conceptual observations using the probability analysis stated in Equations 5.1-5.4 are taken into consideration to determine the existence of various soil types in the tunnel path after analyzing the second part of the geological exploration and analytical study that predicts the existence of soil families along the tunnel direction.

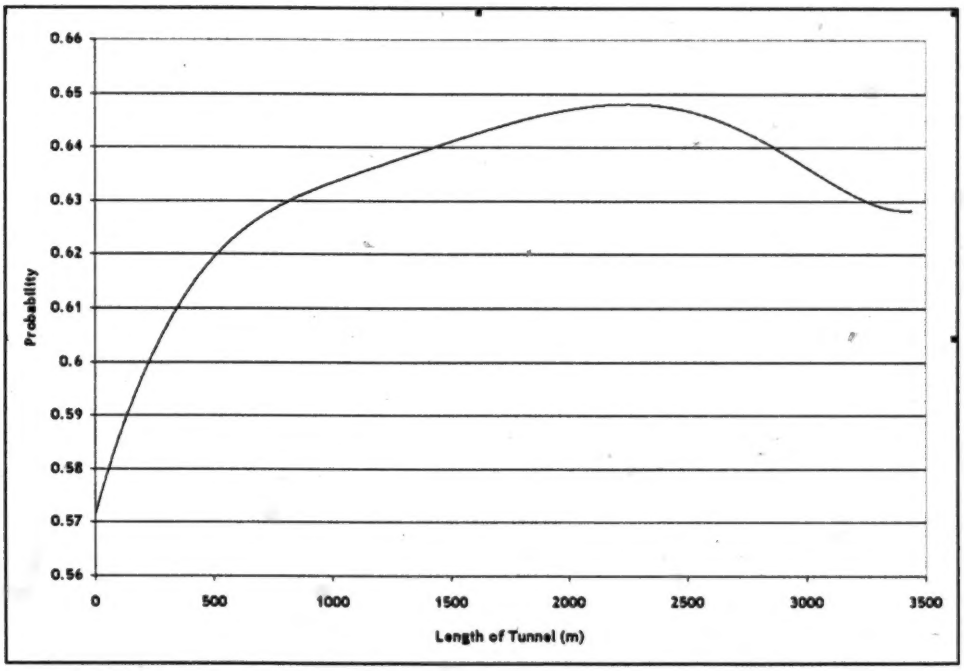


Figure 5-7: Probability of Existence of Soil Type 6 in the Tunnel Path

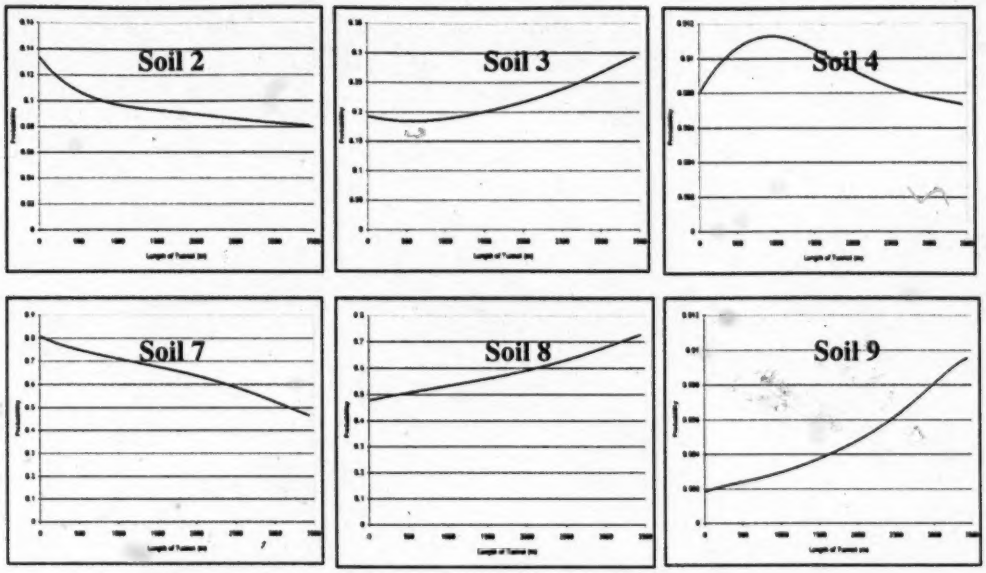


Figure 5-8: Probability of Existence and the Pattern of the Soil Types in the Tunnel

5.6 Prediction of the Soil Families

The general observations and the probability analysis explained so far in this chapter showed ample examples of the co-existence of a particular soil type with many other soil types in an area. Further, it was evident from the cross-sections of the ARC data based on Figure 5-1 that a particular soil exists in the neighbourhood of the boreholes although the borehole does not show any sign of this particular soil. The same principle applies to soil families where one family of soil may co-exist with the other soil families in the neighbourhood as shown in Ruwanpura et al. (2000d). Based on the soil types observed in the area from Kathal and McPherson (1975), several families of soils could be found as explained in Section 5.3. Some of these families co-exist with many other families in the area. The method presented in this section calculates a Weighted Co-Existence Value (WCEV) of a particular soil family in the tunnel's path by considering the following

factors to determine its co-existence with other soil families and to determine the most optimum soil family that could be found at each target point along the tunnel path.

(1) Number of different soil families in the boreholes in the tunnel path or in the close proximity of the tunnel.

(2) Probability of the existence of soil families (appeared in the boreholes within the tunnel path) in the area.

(3) Probability of the existence of a particular soil family compared to the existence of many other families starting from same surficial soil type. For example, the probability of having soil family 51 compared to the many other families generated from the same surficial soil type 5 in the Edmonton area.

(4) Probability of the co-existence of a particular soil family in the neighbourhood of the other soil families in the Edmonton area. For example, the co-existence of family 51 with the family 851 or 751, 7651 in the Edmonton area.

(5) Possibility of having a particular soil family with its neighbouring families by observing its previous soil family and the next soil family along the two axial directions (south to north or north to south, and east to west or west to east).

The following is the methodology used to calculate the WCEV of the soil families for a tunnel construction project.

1. Calculate the probability of the co-existence of a particular soil family in the neighborhood, as shown in the boreholes, with respect to the other soil families within the tunnel area.

2. Calculate the weighted values for soil families at each target point in the tunnel path based on the distances to each of the boreholes in the area and the calculated probabilities in step 1 above.
3. Determine the minimum and maximum weightage values and calculate the WCEV for each of the soil families for each target point along the tunnel. The maximum value of all the WCEV of the families becomes the most probable soil family at each target point.
4. Evaluate the possibility of the various soil families being present according to the knowledge base (available data) in the area. The previous, present, and next families are observed to determine the possible combinations of the soil families in the tunnel's trajectory. If the successive soil families based on the WCEV do not agree with the knowledge base, the next best alternatives are considered. At this stage, it is possible to consider additional soil families generated from the same surficial soil that may co-exist with the soil families in the tunnel area and re-evaluate the logic of the families in the tunnel path based on the knowledge base.

5.6.1 Probability of the co-existence of a particular soil family

The probability of co-existence (PCE_{Base}) of a particular soil family ($Family_{Base}$) in the neighborhood of a borehole in the tunnel area is dependent on the other families ($Family_1$ to $Family_n$) in the boreholes (BH_1 to BH_n) and can be calculated using Equation 5.5 given below. If the $Family_{Base}$ is the same as the soil family in the borehole, the PCE_{Base} value is equal to 1 irrespective of the Equation 5.5.

$$PCE_{Base,\ BH\ i} = \frac{F(Base)_{Soil\ Family}}{(F(Base)_{Soil\ Family} + F(BH\ i)_{Soil\ Family})} \quad \text{.....(5.5)}$$

$F(Base)_{Soil\ Family\ A}$ is the number of occurrences of the base soil family A in the database within a given area. $F(Borehole\ i)_{Soil\ Family}$ is the number of occurrences of the soil family represented in Borehole i, that exists within a given area. The following example illustrates the PCE for Soil family 51 with respect to a borehole BH2 in the tunnel path, which has the soil family 751.

$F(Base)_{51}$ = 18 (Appendix B, Table B1)

$F(BH2)_{751}$ = 14 (Appendix B, Table B3)

$PCE_{51,BH2}$ = 18/32

= 0.5625

Table 5-9 depicts the PCE values for all the families with respect to the boreholes in the tunnel path, as shown in Figure 5-6.

Table 5-9: PCE values with respect to Figure 5-6

Base Soil Family	Neighbouring Boreholes' Soil Family	BH Number	F (Base) Soil Family	F (Borehole) Soil Family	PCE Value
6-5-1	7-5-1	49	3	14	0.1765
	5-1	243	3	18	0.1429
	7-5-1	30	3	14	0.1765
	7-5-6-1	31	3	1	0.7500
	7-5-6-5-1	32	3	5	0.3750
	6-5-1	226	3	3	1.0000
	8-5-6-5-1	51	3	9	0.2500
	8-5-1	50	3	79	0.0366
7-5-1	7-5-1	49	14	14	1.0000
	5-1	243	14	18	0.4375
	7-5-1	30	14	14	1.0000
	7-5-6-1	31	14	1	0.9333
	7-5-6-5-1	32	14	5	0.7368
	6-5-1	226	14	3	0.8235
	8-5-6-5-1	51	14	9	0.6087
	8-5-1	50	14	79	0.1505
8-5-1	7-5-1	49	79	14	0.8495
	5-1	243	79	18	0.8144
	7-5-1	30	79	14	0.8495
	7-5-6-1	31	79	1	0.9875
	7-5-6-5-1	32	79	5	0.9405
	6-5-1	226	79	3	0.9634
	8-5-6-5-1	51	79	9	0.8977
	8-5-1	50	79	79	1.0000
5-1	7-5-1	49	18	14	0.5625
	5-1	243	18	18	1.0000
	7-5-1	30	18	14	0.5625
	7-5-6-1	31	18	1	0.9474
	7-5-6-5-1	32	18	5	0.7826
	6-5-1	226	18	3	0.8571
	8-5-6-5-1	51	18	9	0.6667
	8-5-1	50	18	79	0.1856

Table 5-9: PCE values with respect to Figure 5-5 (Cont.)

Base Soil Family	Neighbouring Boreholes' Soil Family	BH Number	F (Base) Soil Family	F (Borehole) Soil Family	PCE Value
8-5-6-5-1	7-5-1	49	9	14	0.3913
	5-1	243	9	18	0.3333
	7-5-1	30	9	14	0.3913
	7-5-6-1	31	9	1	0.9000
	7-5-6-5-1	32	9	5	0.6429
	6-5-1	226	9	3	0.7500
	8-5-6-5-1	51	9	9	1.0000
	8-5-1	50	9	79	0.1023
7-5-6-5-1	7-5-1	49	1	14	0.0667
	5-1	243	1	18	0.0526
	7-5-1	30	1	14	0.0667
	7-5-6-1	31	1	1	1.0000
	7-5-6-5-1	32	1	1	0.5000
	6-5-1	226	1	3	0.2500
	8-5-6-5-1	51	1	9	0.1000
	8-5-1	50	1	79	0.0125
7-5-6-5-1	7-5-1	49	5	14	0.2632
	5-1	243	5	18	0.2174
	7-5-1	30	5	14	0.2632
	7-5-6-1	31	5	1	0.8333
	7-5-6-5-1	32	1	1	1.0000
	6-5-1	226	5	3	0.6250
	8-5-6-5-1	51	5	9	0.3571
	8-5-1	50	5	79	0.0595

5.6.2 Weightage Factor for a Particular Soil Family at a Target Point in the Tunnel Path

The next step is to calculate a weightage factor for a particular soil family at a target point within the tunnel direction using the distance of the boreholes to the target point and the calculated PCE values for a particular soil family in the respective boreholes. The

weightage factor at Target point T (WF_T) for Soil Family A in the tunnel direction be calculated as per Equation 5.6 where d_{BH} is the distance from Borehole BH to the Target point T and $PCE_{BH,\ Soil\ Family\ A}$ is the PCE Value for Soil Family A at Borehole BH. The use of distances allows a higher weightage value if the target point is closer to the borehole. The weightage factors at the target points along the tunnel path provide a distribution of a particular soil family from the start of the tunnel to the end of the tunnel.

$$WF_{T,\ Soil\ Family\ A} = \frac{\sum_{BH=1}^{n} \frac{1}{d_{BH}} \times PCE_{BH,\ Soil\ Family\ A}}{\sum_{BH=1}^{n} \frac{1}{d_{BH}}} \quad \text{..... (5.6)}$$

5.6.3 Calculation of the WCEV for all soil families at Target Points in the Tunnel Path

This is the final step to calculate the WCEV for all soil families at each target point in the tunnel trajectory using Equation 5.7. The minimum ($WF_{Minimum}$) and maximum ($WF_{Maximum}$) values for all WF values calculated using Equation 5.6 for each soil family are taken into consideration to calculate the WCEV for each family of soils at each target point. The WCEV for Soil Family A at target point T can be calculated as per Equation 5.7. The maximum value of WCEV for soil families becomes the predicted soil family at each target point. Equation 5.7 is a transformation formula to normalize weighted factors calculated using Equation 5.6 and to identify the optimum existence of the soil families along the tunnel path.

$$WCEV_{T,\ Soil\ Family\ A} = \frac{WF_{T,\ Soil\ Family\ A} - WF_{(Minimum)\ Soil\ Family\ A}}{WF_{(Maximum)\ Soil\ Family\ A} - WF_{(Minimum)\ Soil\ Family\ A}} \quad \text{.....(5.7)}$$

As stated earlier, there are several families of soils in the boreholes in proximity to the 3440-meter tunnel. The families are 851, 751, 51, 75651, 7561, 85651, and 651. Figure 5-6 depicts the tunnel and its surrounding boreholes. Figure 5-9 shows the predicted soil families along the length of the tunnel based on WCEV values. The results from Figure 5-9 indicate that the sequence of the soil families are in the order of 751, 51, 7561, 51, 75651, 85651, 651, 85651, and 851 (Table 5-10).

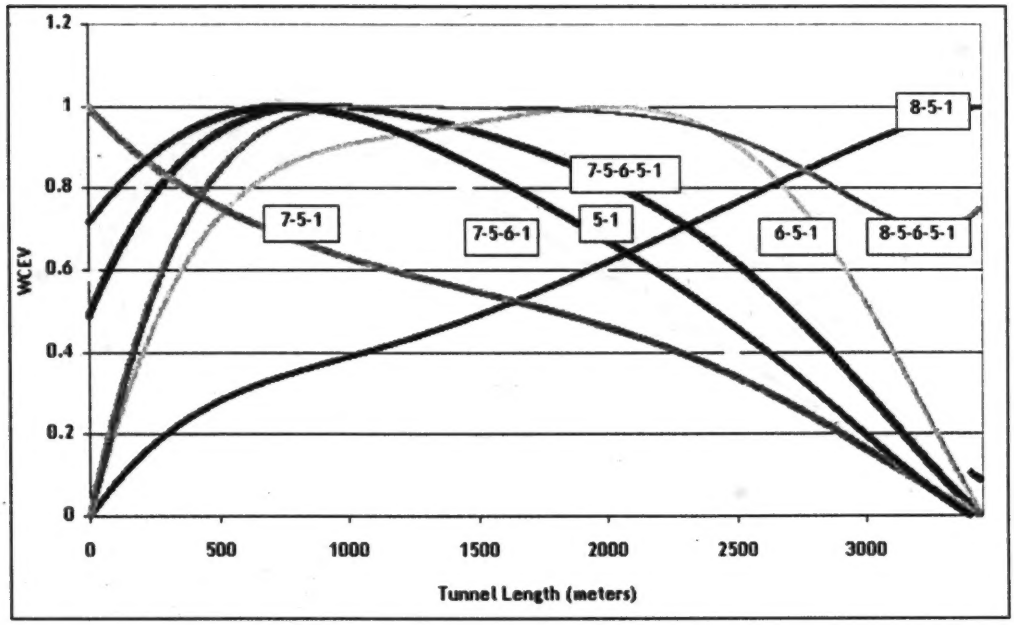


Figure 5-9: WCEV of the Soil Families for Sample Tunnel Project

Table 5-10: Soil Families in the Tunnel Direction based on WCEV

Soil Family	Interval (m)
751	0-220
51	221-479
7561	480-719
51	720-823
75651	824-998
85651	999-1794
651	1795-2420
85651	2421-2761
851	2762-3443

5.6.4 Final Evaluation of Soil Families in the tunnel Direction

At this stage, the results in Table 5-10 are re-evaluated using the knowledge base in the area. The previous, present, and next families in the area are referenced to determine the possibility of having the sequence shown in Figure 5-9. Appendix "D" provides the present, past, and next families for the soil families of 751, 51, 7561, 75651,85651,651 and 851. Following are the observations:

1. It is improbable that Soil family 7561 exist between soil families 51 on either side.
2. It is improbable that Soil family 85651 exist between soil family 851 and soil family 651.
3. Although soil family 651 exists between family 85651 on either side, it is improbable that soil family 75651 exist when soil family 85651 is on one side and soil family 51 is on the other side.

These observations lead to amend the predicted results and look for the next best alternatives. The amended and final sequence is 751 (0 to 220 meters), 51 (221 to 823 meters), 75651 (824 to 998 meters), 651 (999 to 2420 meters) and 85651 (2421 to 3440 meters) in the tunnel trajectory. The prediction of soil family results show that both soil type 1 and 5 are continuous throughout the tunnel. Soil type 6 could only be found from 824 meters until the end of the tunnel. The surficial soil types in the tunnel path are in the order of soil 7, soil 5, soil 6, and soil 8 from the start to the end of the tunnel. At this stage further explorations are performed to identify the possibility of encountering other soil families that may co-exist with the existing soil families. For example, soil family 5651 could occur between soil families 51 and 75651, as it may not be possible that surficial soil 7 and soil type 6 within soil layer 5 appear together. The same logic can be applied as to the existence of 5651 between 651 and 85651. A new test could then be performed to find out whether 5651 exists in the tunnel. The steps explained in Equations 5.5 to 5.7 were then applied to determine the existence of family 5651. However, the results show that 5651 does not exist in the tunnel path.

The probability of the existence of soils discussed in Section 5.5 and the predicted soil families in this section are compared to derive the final conclusions. The existence of Soil 1, 5, 6, and 7 was evident from Section 5.5. Having the soil family 751 in the first part of the tunnel (0 to 220 meters) and having 75651 from 824 to 998 meters strongly supports the diminishing probability of soil 7 from the start to the end of the tunnel (see Figure 5.8). The existence of soil 6 increases from the start of the tunnel to a peak around 2330 meters and then drops down marginally until the end of the tunnel according to the analysis in Section 5.5. Soil family analysis further proves the existence of soil 6 by

having the soil families 75651, 651 and 85651 from 884 meters toward the end of the tunnel.

5.7 Application of the Prediction of Soil Families for actual tunnel projects

The method of predicting soil families was tested using two actual tunnel construction projects. The first project is the Mill Woods Drainage Improvement - Phase III tunnel. The second project is the proposed North Edmonton Sanitary Truck (NEST) tunnel project in Edmonton.

5.7.1 Application to Mill Woods Tunnel Project

The details of the boreholes in the tunnel path or closer to the tunnel path are shown in Table 5-11 and the locations of the boreholes are in Figure 5-10. All of these boreholes contain continuous soil types such as soils 7, 5 and 1. Along the tunnel path, there are two basic families, family 751 and family 51. The first portion of the tunnel project is soil family 51 (borehole 177) and then has family 751 until it reaches the curve (borehole 185). The second portion of the tunnel has a mix of soil families 751 and 51 (from borehole 186 to borehole 194). Figure 5-10 shows the predicted soil families based on the method explained in this chapter for the last segment of the tunnel. This analysis shows that the soil families could be predicted using this analytical method. However, it is not possible to validate results until new boreholes are driven. This particular project was constructed in 1994/95.

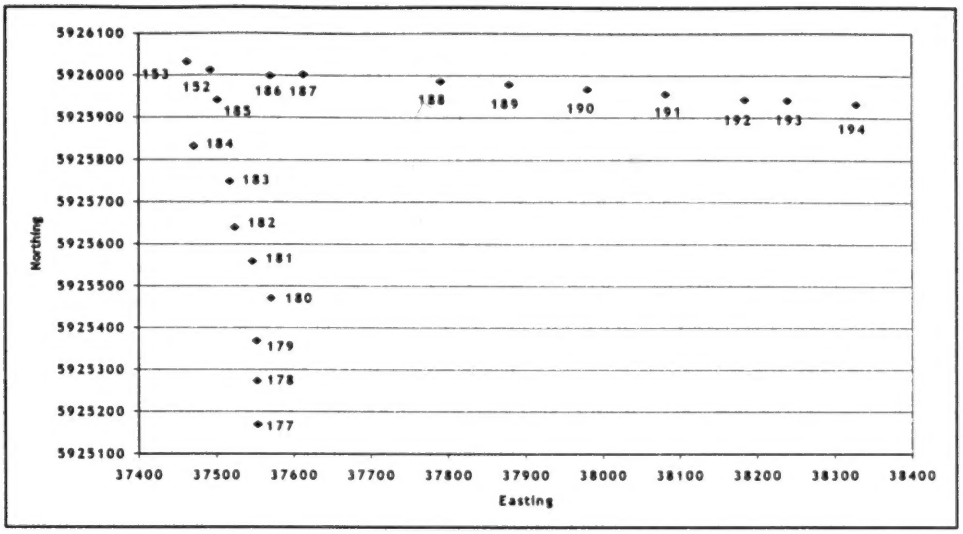


Figure 5-10: Boreholes of the Mill Woods Tunnel Project (Not to Scale)

Table 5-11: Borehole details for Mill Woods Tunnel Project

BH No	Easting (m)	Northing (m)	Family
177	37553	5925169	51
178	37552	5925273	751
179	37551	5925368	751
180	37570	5925471	751
181	37546	5925559	751
182	37524	5925640	751
183	37517	5925749	751
184	37471	5925833	751
185	37501	5925941	751
153	37462	5926032	751
152	37492	5926012	751
186	37570	5925999	751
187	37613	5926003	51
188	37791	5925986	751
189	37879	5925979	751
190	37980	5925967	51
191	38081	5925957	51
192	38184	5925943	51
193	38238	5925941	751
194	38327	5925932	51

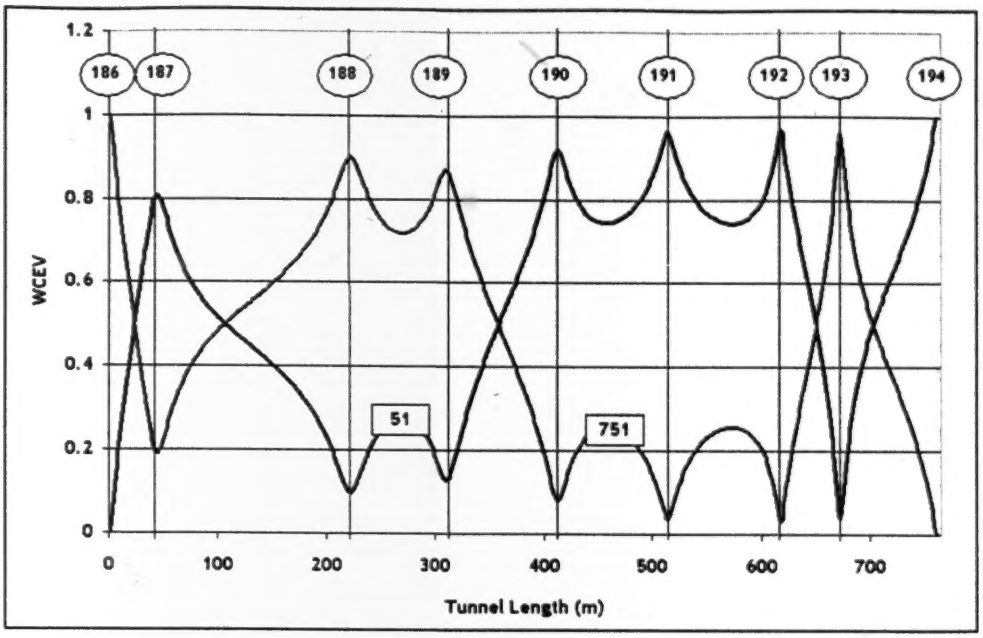


Figure 5-11: WCEV of the Soil Families for Mill Woods Tunnel – Last Portion

Figure 5-11 shows the prediction of either soil family 751 or soil family 51 along the tunnel path. Soil family 751 prevails over soil 51 within the intervals of 0-23 meters, 107-357 meters, and 651-702 meters. This prediction method allows the engineers to decide whether they need any additional boreholes along the tunnel path to reduce the uncertainty of encountering difficult soils between the boreholes.

5.7.2 Application to NEST tunnel Project

The NEST tunnel project initially had few boreholes driven along the tunnel path. Figure 5-12 (not to scale) shows the location of the initial boreholes driven for the project and

the additional borehole data obtained from ARC data closer to the tunnel path. Details of the boreholes are given in Table 5-12. The entire tunnel is about 1650 meters long. The methodology presented in this chapter was applied to determine the probability of existence of non-continuous soil types in the last 708 meters of the tunnel.

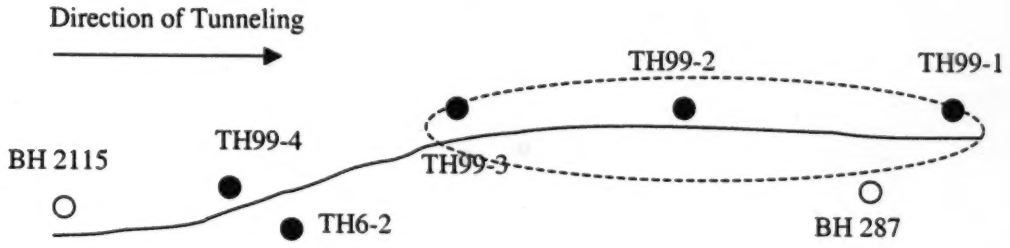


Figure 5-12: Location of preliminary boreholes for NEST tunnel (not to scale)

Table 5-12: Details of preliminary boreholes for NEST tunnel

BH No	Easting	Northing	Family	Source
TH99-1	30392	5942816	8565251	City of Edmonton
TH99-2	30793	5942806	8565251	City of Edmonton
TH99-3	31087	5942801	85251	City of Edmonton
TH99-4	31419	5942631	851	City of Edmonton
TH6-2	31308	5942554	851	City of Edmonton
BH287	30350	5942460	85251	ARC
BH2115	32667	5942520	851	ARC

The last 708 meters, as shown in Figure 5-12, contain several non-continuous types of soils including soil 6 and soil 2 in the boreholes TH99-1 to TH99-3. The elevation of both soil 2 and soil 6 are within the thickness of the tunnel or just below the tunnel's bottom elevation. The purpose of the analysis was to identify the potential extent of these non-continuous soil types. The first portion of the tunnel showed only family 851 in all

boreholes (both City of Edmonton and ARC). However, the ARC borehole BH287 that belongs to soil family 85251 is about 370 meters away from the tunnel. Since BH287 has no evidence about the existence of soil type 6, and the distance between TH99-1 and TH99-2 is approximately about 400 meters, the prediction of soil families was performed to discover the following.

1 Extent of soil type 6 between TH99-1 and TH99-2

2 Extent of soil type 2 between TH99-1 to TH99-3.

An analysis performed for the last portion of the tunnel using the methodology stated in this chapter and submitted to the City of Edmonton design and construction department concluding the following, based on the WCEV graph shown in Figure 5-13:

1 Soil Family 8565251 only exists about 54 meters from the Borehole TH99-1 toward the TH99-2 borehole and for only 67 meters in the area of Borehole TH99-2. This suggests that Soil 6 is not a continuous soil layer between TH99-1 to TH99-2.

2 Soil Family 85251 is the most likely soil family for 264 meters from borehole TH99-3 toward the end of the tunnel and then for 321 meters between the boreholes TH99-2 and TH99-1.

The analysis also recommended that the City of Edmonton should consider exploring the soil conditions further, especially between boreholes TH99-1 and TH99-2.

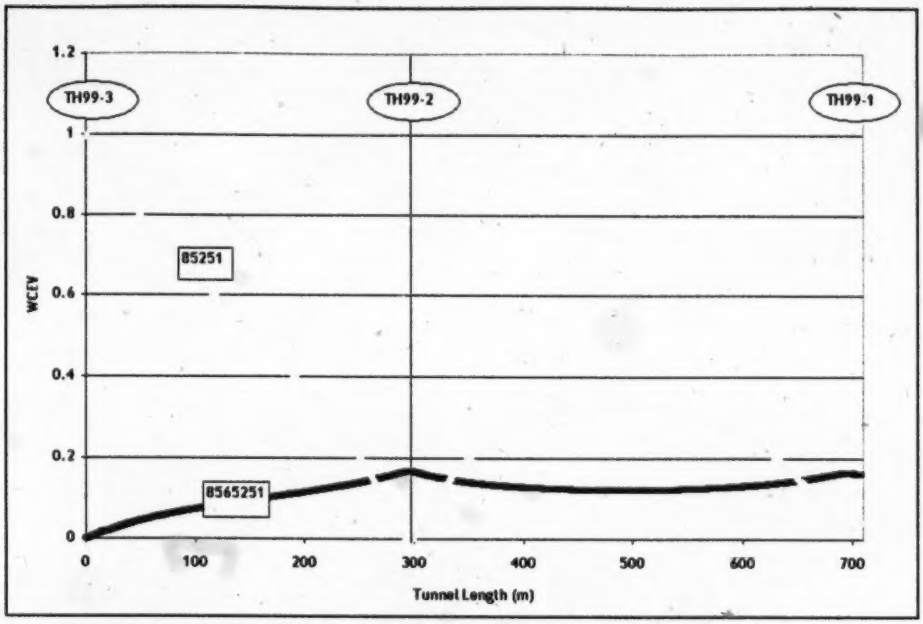


Figure 5-13: WCEV for NEST tunnel's last 708 meters

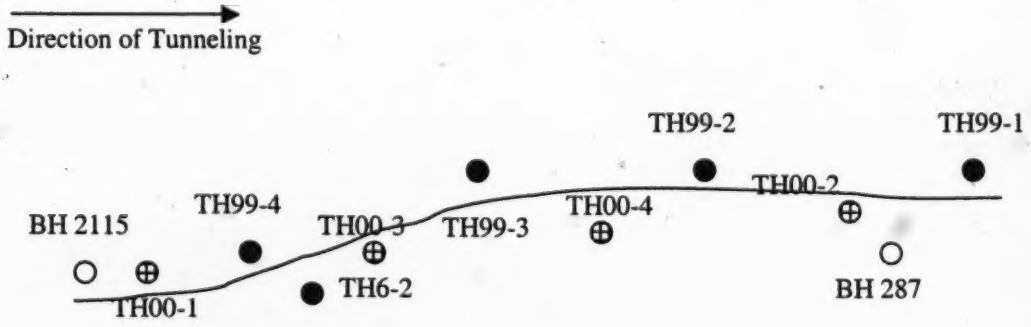


Figure 5-14: Location of all boreholes for NEST tunnel (not to scale)

City of Edmonton further explored the soil conditions along the tunnel path by driving four additional boreholes (TH00-1 to TH00-4) as shown in Figure 5-14. Borehole TH00-3 belongs to soil family 851 whereas all other boreholes belong to soil family 85251. The

TH00-2 borehole confirmed the prediction of not having soil 6 continuously from TH99-2 to TH99-1 although both TH99-1 and TH99-2 contain soil 6. Further, the existence of soil family 85251 in boreholes TH00-4 and TH00-2 confirmed that soil 2 is continuous from the left of TH99-3 to TH99-1. This prediction and analysis is a clear indication of the validity of the methodology proposed in this chapter for hypothetical tunnel construction projects. This method can used by engineers to explore the soil types along the tunnel path in addition to the usual geological explorations performed.

5.8 The influence of the prediction of the soil families to assess the transitions of soils along the tunnel path

Chapter 6 discusses the transitions of soils along the tunnel path. This section explains how the prediction of soil families could assist in assuming the soil profiles logically between the boreholes to determine the transitions of soils along the tunnel path. Figure 5.13 shows the existence of soil family 8565251 and soil family 85251 along the tunnel path of the NEST tunnel. Figure 5.14 and the related analysis validated the prediction shown in Figure 5.13. According to Figure 5.13, the tunnel length between the borehole TH99-3 and TH99-1 can be divided into four sections based on the existence of the soil families as shown in Figure 5.15.

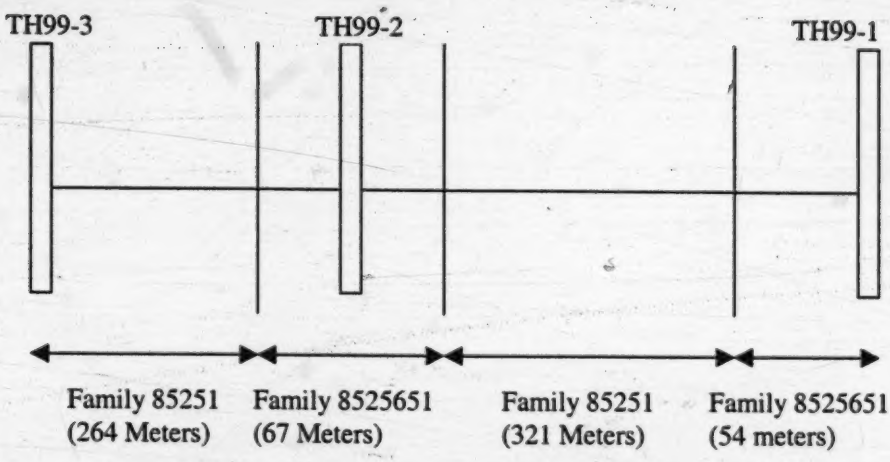


Figure 5.15: The existence of different soil families for NEST Tunnel Project

Based on the soil prediction methodology explained in this chapter, soil family 85251 is present in the first 264 meters from borehole TH99-3. Soil family 8565251 then exists for 67 meters followed by soil family 85251 for another 321 meters. The last 54 meters is comprised of soil family 8565251. According to Figure 5.14, there are two new boreholes within the 708 meters of tunnel length. Borehole TH00-4 is about 169 meters from TH99-3, and borehole TH00-2 is about 105 meters from borehole TH99-1. The WCEV graph predicted for the NEST tunnel was reproduced using these two new boreholes to further justify the extent of the length of the soil families along the tunnel. Figure 5.16 shows the new WCEV graph for the tunnel.

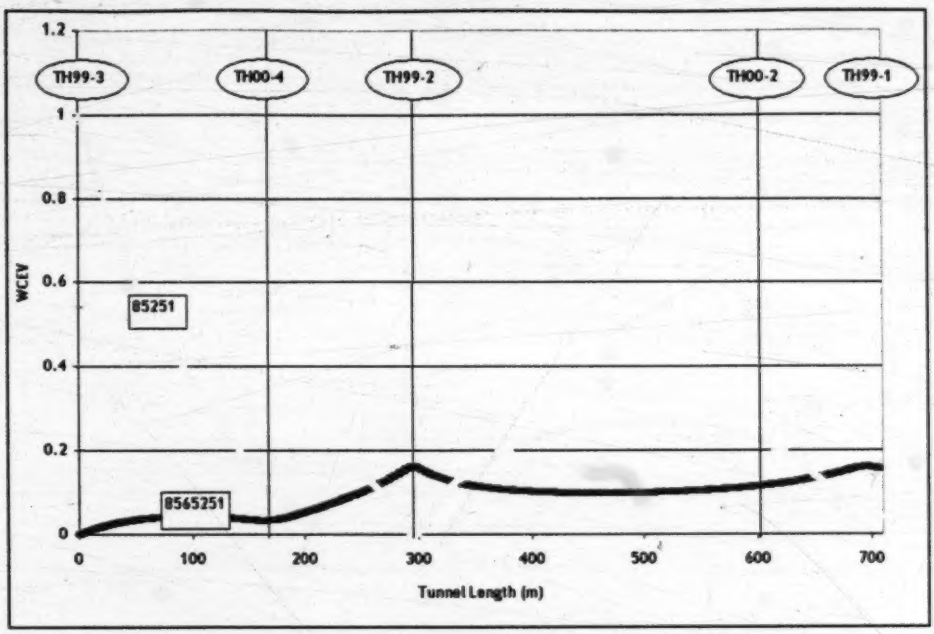


Figure 5.16: The new WCEV for NEST tunnel's last 708 meters

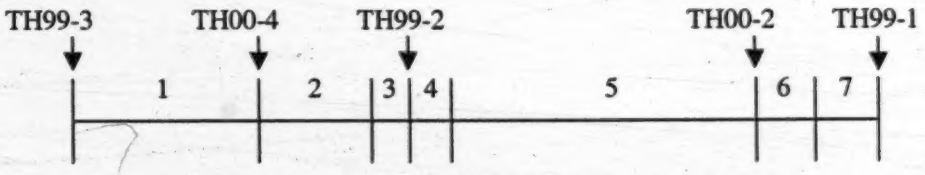


Figure 5.17: Sections of the tunnel with different soil families

Based on the new WCEV graph and the availability of new boreholes, this tunnel portion can be divided to following seven sections, as shown in Figure 5.17:

a) Section 1: 165 meters in Soil Family 85251

b) Section 2: 99 meters in Soil Family 85251

c) Section 3: 30 meters in Soil Family 8565251

d) Section 4: 37 meters in Soil Family 8565251

e) Section 5: 271 meters of Soil Family 85251

f) Section 6: 52 meters of Soil Family 85251

g) Section 7: 54 meters of Soil Family 8565251

Because of the analysis of the prediction of the soil families, it was possible to reduce the uncertainty of the soil conditions between the boreholes by identifying the extent of each of the soil families. Figure 5.18 shows the actual soil profiles of each of the boreholes only considering the availability of boreholes TH99-1, TH99-2, and TH99-3 in the very early stage (as in Figure 5.12) of the project. The main soil types available in the tunnel path are Glacial Clay Till (soil type 5), reworked Clayshale (soil type 2) and sand pockets (soil type 6).

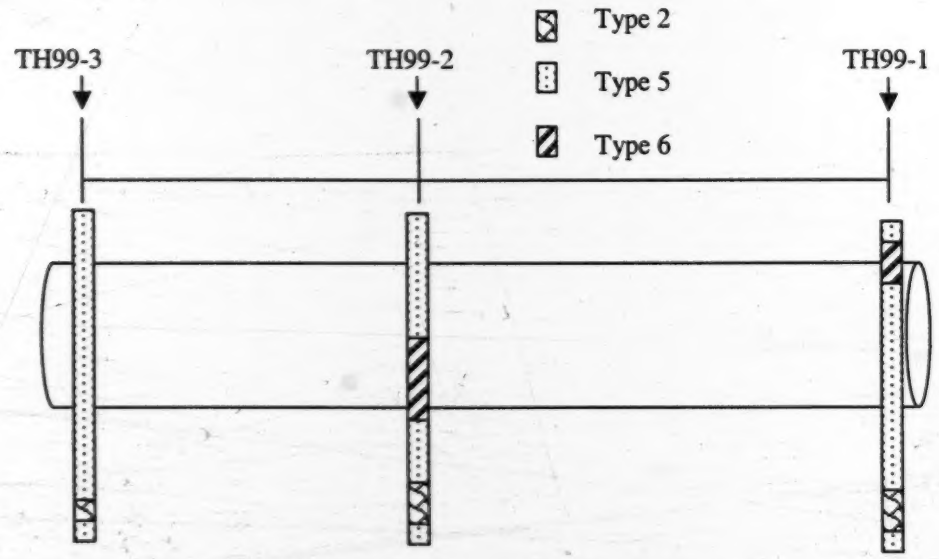


Figure 5.18: Details of the boreholes and the tunnel (first stage)

According to Figure 5.18, it could be assumed that soil type 6 exists continuously from some point on the left of borehole TH99-2 to the right of borehole TH99-1. It also shows that soil 2 does not exist in the tunnel path. Figure 5.19 shows one of the most likely

profiles of soils 2 and 6 between the boreholes using linear approximations or interpolations.

The analysis explained in the chapter proved that soil type 6 does not exist continuously. Because of the analysis in section 5.7 and the availability of new boreholes, it is easier to determine the soil profiles more accurately and logically between the boreholes. Figure 5.20 shows the most likely profiles of soil types 2 and 6 within soil type 5 along the tunnel path based on the soil family prediction methodology.

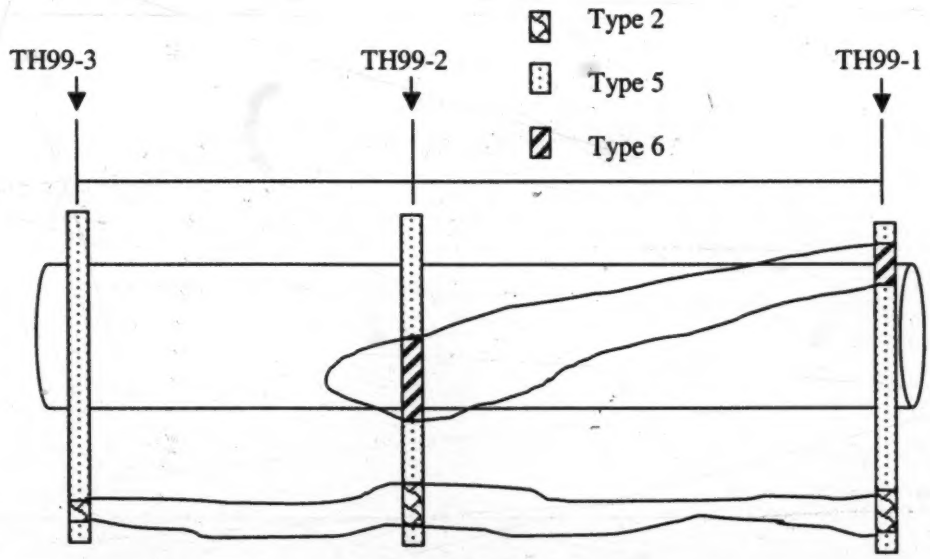


Figure 5.19: Assumed soil profiles between the boreholes without the proposed analysis

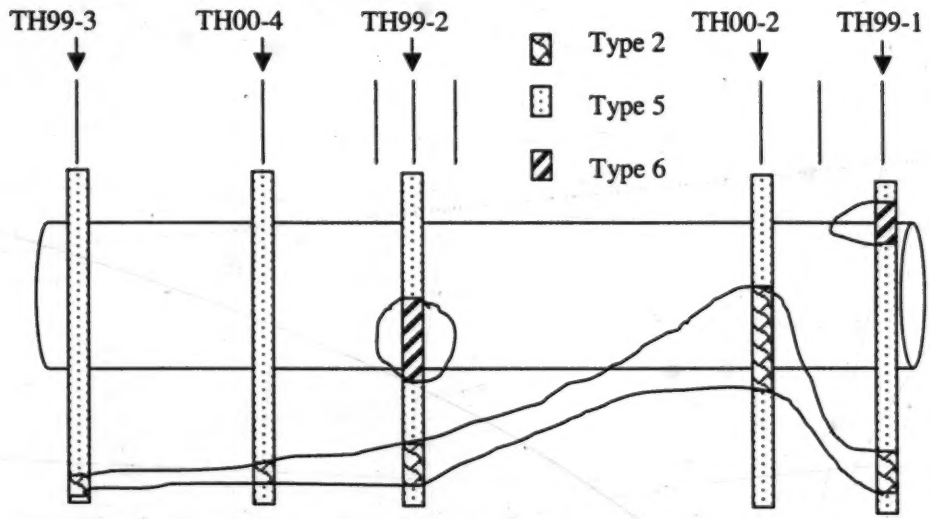


Figure 5.20: Assumed soil profiles between the boreholes based on the proposed analysis

Figure 5.20 can be divided into several segments to determine the transition from one soil to another and the modeling algorithms of soil transitions to be implemented within special purpose simulation as explained in Chapters 6 and 7. The results shown in this section further prove that this technique is very useful to predict the non-continuous soil layers (soil pockets) along the tunnel path.

5.9 Limitations on Borehole Data used in the Study

The ARC data used for the study are typically spaced on a 1-mile grid system, as explained in Section 5.2. Since the boreholes are not in close proximity, there could be errors in judgment in predicting soil types or soil families. During the preliminary stage of the study, the study area was investigated to divide it into identifiable clusters.

5.10 Conclusions

This chapter presented a soil characterization and prediction methodology that accounts for geologic data for tunnel construction operations. The methodology uses a quantitative and analytical approach of predicting soil types that are beneficial to the project planners and engineers. The analysis is presented with an intention of how this analysis could be useful for construction purposes. This analysis also compliments the geotechnical explorations conducted for tunnel construction projects.

The methodology presented in this chapter could be applied to any area. However, Edmonton geology has been used as the base area to illustrate the prediction concepts and methodology. After the preliminary characterization of the soils, a concept of soil families was introduced along with soil clusters commencing from the surficial soil type in any given area. The first part of the probability analysis predicted the existence of a particular soil, co-existence of a soil with other soils under different soil clusters and then the probability of the existence of a soil along the tunnel path. The second portion of the probability analysis predicted the combination of soil families and their distribution and thereby identified the existence of soil families along the tunnel path. This prediction provides an insight to two areas. Since the prediction of the soil families are established using an analytical method, it will provide further research towards developing an analytical method to predict the elevation of the soils using the concept of soil families. An accurate prediction of the elevations could further allow the end users to determine the distribution of the soil profiles between the boreholes. Secondly, this method enables the engineers to further analyze the geological explorations for construction purposes. A hypothetical example shown later in the chapter proved that engineers could use this

analysis to compliment the typical geological explorations conducted for a tunnel construction project.

NEST tunnel analysis proved how the prediction of soil families could help to accurately assess the soil profiles to determine the transitions of soils along the tunnel path for simulation purposes, as explained in Chapters 6 and 7. The use of this analysis for hypothetical tunnel construction will reduce the uncertainty of the project by logically investigating the soil types in the tunneling path before commencing the actual construction. It also provides an opportunity for the construction engineers and managers to get acquainted with the possible occurrence of soil types along the tunnel path that could be very useful for applications in project scheduling and estimating for tunnel construction operations. Although the application of this method was limited to Edmonton geology, the method can be used for any other city or area provided that the city or area has adequate published data or borehole data from past tunnel construction projects.

Chapter 6: Prediction of Soil Transitions for Special Purpose Tunnel Simulation using Transitional Probabilities

6.1 Introduction

The prediction of soil types along the tunnel path is a challenging task due to uncertainty and the unavailability of deterministic data along the tunnel path. The boreholes driven for a tunnel construction project only provide a handful of deterministic information at discrete locations either in the tunnel alignment itself or adjacent to the tunnel trajectory. The borehole data determines the soil types at discrete locations, and produces deterministic estimation of the soil types and the elevations of each of the soil layers in the boreholes. The geological exploration and site characterization in the vicinity of the tunnel discussed in Chapter 5 provides additional information and reduces the uncertainty of the actual soil conditions between the boreholes along the tunnel.

Section 4.2.2 shows a simulation example where the soil types were arbitrarily used for simulation using deterministic borehole data. The tunnel simulation template described in Chapters 3 and 4 does not have the ability to extract the soil conditions accurately. The end-user could only specify the approximate percentage of each soil layer based on the borehole data. Hence, the productivity and tunnel advance rate predicted by the template do not provide conclusive outputs for accurate prediction of productivity. The approach described in this chapter predicts the transition of soils along the length of the tunnel and provides an analytical method for the tunnel simulation template to calculate the boring rate (tunnel excavation rate). The other input parameters such as

swell factor, composition of soils along with the soil transition points along the tunnel path then determine the productivity of tunnel construction operations. Markov theory is used to create the transitional probabilities to predict the soil transition points. The use of transition probabilities for simulation comprises three stages. The end result of the first stage will affect the results of the second stage.

a) Calculation of transitional probabilities.

b) Modeling Algorithm modules based on the transition scenarios of the soils.

c) Application of the modeling algorithms within tunnel simulation template.

This chapter discusses only a) and b) above. Part c) is discussed in Chapter 7. Section 6.2 explains the concept of Markov theory using a soil transition example. Section 6.3 presents the methodology to calculate the transitional probabilities. Section 6.4 discusses a modified modeling approach to calculate the transition of soils using the Markov probabilities. Section 6.4 also provides the complete algorithm for one of the scenarios of transition modules. The additional algorithms for other scenarios are in Appendix "D". The limitations and further improvements are stated in Section 6.5. Section 6.6 discusses the conclusions.

6.2 Concept of Markov Theory

Figure 6-1 is used to explain the concept of Markov theory and various terminologies, which provide a clear explanation of the modeling algorithms and the method of calculating the transitional probabilities. Figure 6-1 shows a typical scenario of transiting soil types between three borehole locations along the tunnel path. The locations could be

known boreholes or artificial boreholes (see Appendix "A" for terminologies) based on the methodology described in Chapter 5.

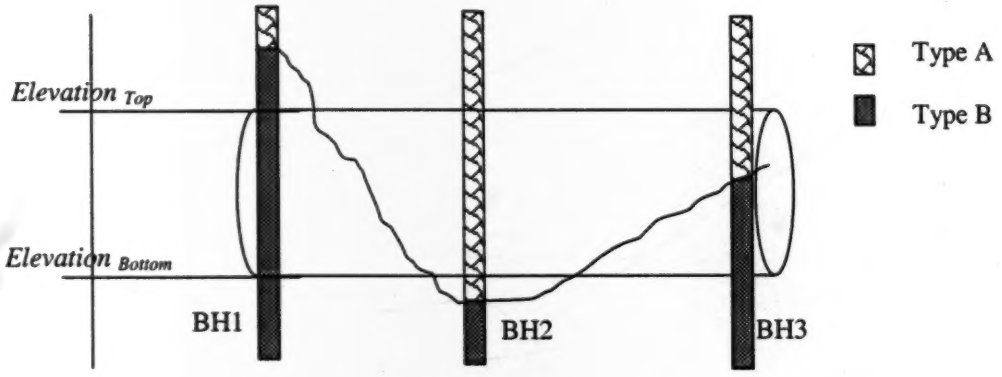


Figure 6-1: Transition of Soil A and Soil B between boreholes

A simple two-state (type A soil, type B soil) Markov chain can be used to determine the occurrence of type A or type B. Figure 6-1 shows that the transition from type B to type A both at the top elevation (*elevation* $_{Top}$) and bottom elevation (*elevation* $_{Bottom}$) of the tunnel between boreholes BH1 and BH2. The transition from Soil A to Soil B can be evident only from the bottom elevation of the tunnel between boreholes BH2 and BH3. This two-state Markov chain is defined by transitional probabilities of moving from one soil state to another soil state. Transitional probabilities are dependant on the location of the tunnel, diameter of the tunnel, start and end elevations of the soil types, and the soil types in the vicinity. Equation 6.1 defines the transitional probability of transiting from state *b* (Soil B) on one known point (BH1) in the tunnel to state *a* (Soil A) on immediate known point (BH2) in the tunnel at top elevation of the tunnel (*elevation* $_{Top}$).

$$P_{Top}(b/a) = \frac{N_{ba}}{n_b} \quad \text{.....(6.1)}$$

N_{ba} is the number of observed transitions generated from Soil B to Soil A at *elevation* $_{Top}$ along the tunnel path. The number of observed transitions generated from Soil B to all states including Soil A and Soil B at *elevation* $_{Top}$ is denoted by n_b. When two types of soil interact within the tunnel alignment, four (4) transitional probabilities must be defined:

$P_{Top,\ BH2}$ (A/A) Probability of Soil A at *Location BH2* in the tunnel path at *elevation* $_{Top}$ given that Soil A can be observed at *Location BH1* at *elevation* $_{Top}$.

$P_{Top,\ BH2}$ (A/B) Probability of Soil B at *Location BH2* in the tunnel path at *elevation* $_{Top}$ given that Soil A can be observed at *Location BH1* at *elevation* $_{Top}$.

$P_{Top,\ BH2}$ (B/A) Probability of Soil A at *Location BH2* in the tunnel path at *elevation* $_{Top}$ given that Soil B can be observed at *Location BH1* at *elevation* $_{Top}$.

$P_{Top,\ BH2}$ (B/B) Probability of Soil B at *Location BH2* in the tunnel path at *elevation* $_{Top}$ given that Soil B can be observed at *Location BH1* at *elevation* $_{Top}$.

The probability of observing Soil A (*state a*) in the tunnel path at *elevation* $_{Top}$ can be calculated with Equation (6.2).

$$P_{Top}(a) = \frac{N_{Top}(a)}{T_{Top}} \quad \text{.....(6.2)}$$

Number of observed transitions in Soil A at tunnel elevation Top is denoted by $N_{Top}(a)$. T_{Top} denotes the total number of all soil types observed along the tunnel path at elevation $_{Top}$.

There are two overall probabilities to define the model in detail for one elevation, which is listed below.

P_{Top} (A) Overall probability of having Soil A at *elevation* $_{Top}$

P_{Top} (B) Overall probability of having Soil B at *elevation* $_{Top}$

6.3 Calculation of Transitional Probabilities

6.3.1 Basic Rules in Creating Transitional Probability Matrices

According to Krumbein and Dacey (1969) and many other researchers, geological observations can be structured as Markov chains in two main ways, both of which have been used in stratigrahic analysis (see Chapter 2 for details). The first approach considers the lithology (or soil type) at discrete points that are spaced equally along a vertical profile. The points are numbered consecutively, and the use of Markov chains is based on the assumption that the lithology at point *n* depends upon the lithology at the preceding point *(n-1)*. Because the same lithology may be observed at successive points, the transition matrix that gives the probability of moving from one lithology to another generally has nonzero elements on the main diagonal. The second approach considers only the succession of lithologies, and because each transition is moving to a different lithology within the system, the diagonal elements are all zero (i.e. both P (A/A) and P

(B/B) are zero). Table 6-1 shows examples of these two types of matrices produced by Krumbein and Dacey (1969) for the same stratigrahic section that contains four lithologic components. The matrix on the left (Table 6-1 a) is a Markov chain which gives the transitional probabilities between successive vertical observations spaced at 2 feet apart, so that the diagonal probabilities P_{ii} are nonzero. The calculation of the spacing is difficult, as it does not have a proper methodology. This was stated by Schwarzacher (1969) and many other researchers. Schwarzacher (1969) performed a trial and error experiments to determine the spacing of the lithology to study sedimentary cycles in Kansas. The matrix on the right (Table 6-1 b) is an embedded Markov Chain (as explained in Chapter 2) which gives the transition probabilities only between the successive lithologic units, and hence the P_{ii} are identically zero. These two ways of structuring transition matrices involve some fundamental differences that are explicitly taken into consideration in calculating the transitional probabilities of the proposed soil transition method.

Table 6-1: Transition Probability Matrices for a) Markov Chain (Left) and Embedded Markov Chain (Right) [a]

	A	B	C	D
A	0.787	0.071	0.075	0.067
B	0.048	0.788	0.061	0.103
C	0.105	0.316	0.430	0.149
D	0.182	0.388	0.132	0.298

	A	B	C	D
A	0	0.333	0.352	0.315
B	0.226	0	0.288	0.486
C	0.184	0.554	0	0.149
D	0.269	0.553	0.188	0

[a] *Source: Krumbein and Dacey (1969) and Scherer (1968)*

The embedded Markov chain method is rejected for the proposed soil transition modeling algorithm modules as the purpose of the transitional probabilities is to determine the transition point between two locations. The other Markov chain calculation method is also modified in the proposed model. Further the proposed method uses the transitional probabilities calculated along the tunnel path rather than along the boreholes vertically. When calculating the transitional probabilities, the interval for which the observations are made have an impact on the values. If the interval is fixed and too short, the resulting diagonal transitional probabilities may be more biased than other transitional probabilities. For example, if the total length between the two locations is 100 meters and if there is only one transition between soil type A and B at 45 meters at the top of the tunnel elevation and if the observations are made at every 1 meter, the P (A/A) = 0.99 and the P (A/B)=0.01. However, if the fixed interval is set for 10 meters, P (A/A) = 1.0 and P (A/B) = 0. Hence, the proposed method does not consider a fixed interval at all.

6.3.2 Assess the Soil Profiles between the boreholes

Since the certainty is only with the known boreholes or additional points along the tunnel (based on method in Chapter 5), the observations are made at the known borehole locations and the additional points (referred as "transition boundary points"). For example, the soil prediction method described in Section 5.7 shows additional points along the tunnel path for the NEST tunnel. Figure 6-2 shows NEST tunnel's last 708 meters with 5 actual boreholes and 3 transition boundary points (denoted by TB) locations along the tunnel path. The transition boundary points were determined based on the soil prediction method explained in Section 5.7.

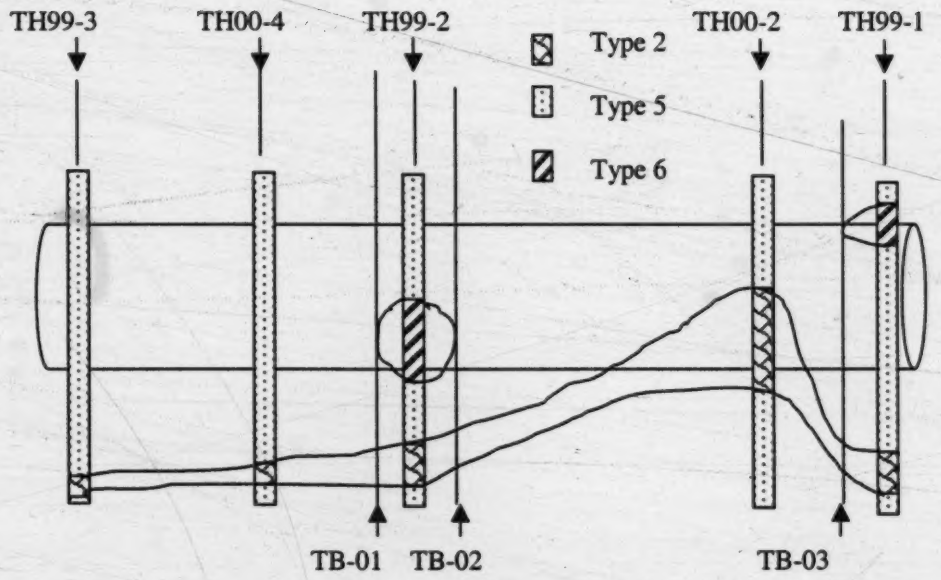


Figure 6-2: Actual and artificial boreholes along the tunnel path (NEST project)

Because of the transition boundary points, the tunnel is divided into the following seven sections. The following are the sections (from left to right) and the types of transitions.

1. Section 1: No transition either at top or bottom of the tunnel.
2. Section 2: No transition either at top or bottom of the tunnel.
3. Section 3: Transition from Soil 5 to Soil 6 at bottom elevation of the tunnel.
4. Section 4: Transition from Soil 6 to Soil 5 at bottom elevation of the tunnel.
5. Section 5: Transition from Soil 5 to Soil 2 at bottom elevation of the tunnel.

6. Section 6: Transition from Soil 2 to Soil 5 at the bottom elevation of the tunnel.
7. Section 7: Transition from Soil 5 to Soil 6 at the top elevation of the tunnel.

The start and end elevations of each of the soil layers determine the direction of the soil profiles between known or artificial boreholes. Prediction of the elevation of soils at a target point along the tunnel path using the start and end elevations of the soils in the boreholes and the distance from each of the boreholes to the target was proposed by various researchers, including Isaaks and Srivastav (1989) and Allouche (2001). The successful prediction of soil elevations could provide an accurate understanding of the direction of the soil profile.

Transitional probabilities are calculated along the length of the tunnel at assigned elevation levels based on the observations of each of the known or artificial boreholes. If the predicted soil profiles using either Allouche (2001) or Isaaks and Srivastav (1989) show any changes in the direction of the soil profile between the two boreholes, an additional observation is considered (artificial borehole) in between the boreholes to reflect the change in the direction of the soil profile. Figure 6-3 shows an example of a possible case. According to BH1 and BH2 data, it could be assumed that the profile of Soil B only transits at the bottom of the tunnel elevation and the start elevation of Soil A reduces from BH1 to BH2. However, prediction of each of the soil types estimates a different profile which shows that the start elevation of Soil B may increase and then decrease between BH1 and BH2 (Figure 6-4).

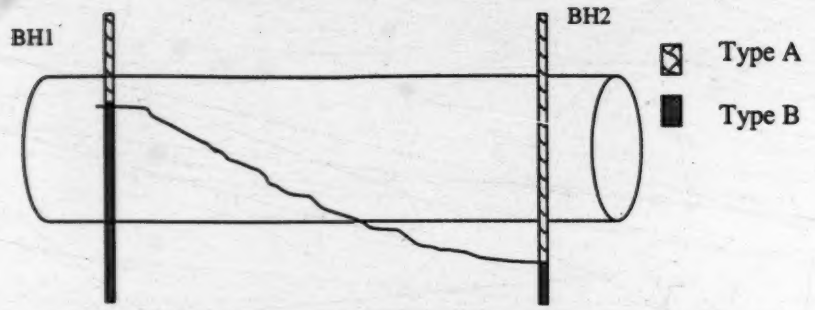


Figure 6-3: The estimated profile only based on the two boreholes

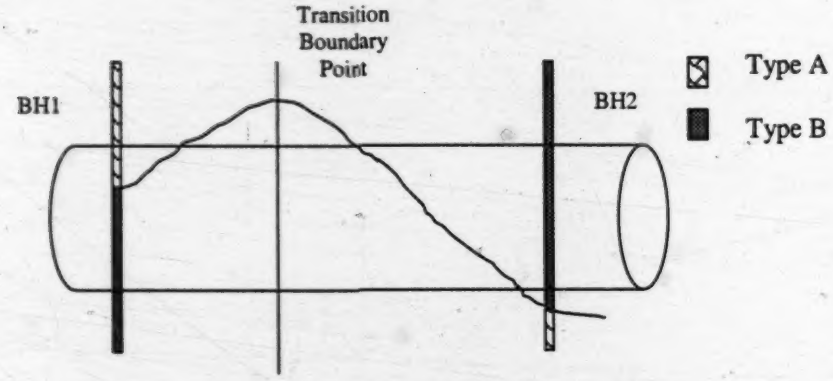


Figure 6-4: Estimated profile with an artificial borehole

Because of the change in direction between BH1 and BH2, an additional observation point (transition boundary point) is adopted allowing a division between BH1 and BH2. The data in the artificial BH is also taken in consideration when calculating the transitional probabilities. With this new artificial, the scenario of only transiting at the bottom between BH1 and BH2 change to;

a) Between BH1 and Artificial BH: Transitions at Top (Direction = Up)

b) Between Artificial BH: Transitions both at top and bottom (Direction=Down)

6.3.3 Rules in Transitional Probability Matrices for Soil Prediction (Two Continuous Soils)

The following are the rules for calculating the transitional probabilities. Figure 6-5 is used to explain the rules in modified Markov transitional probabilities. Figure 6-5 is a hypothetical sample of actual boreholes and artificial boreholes.

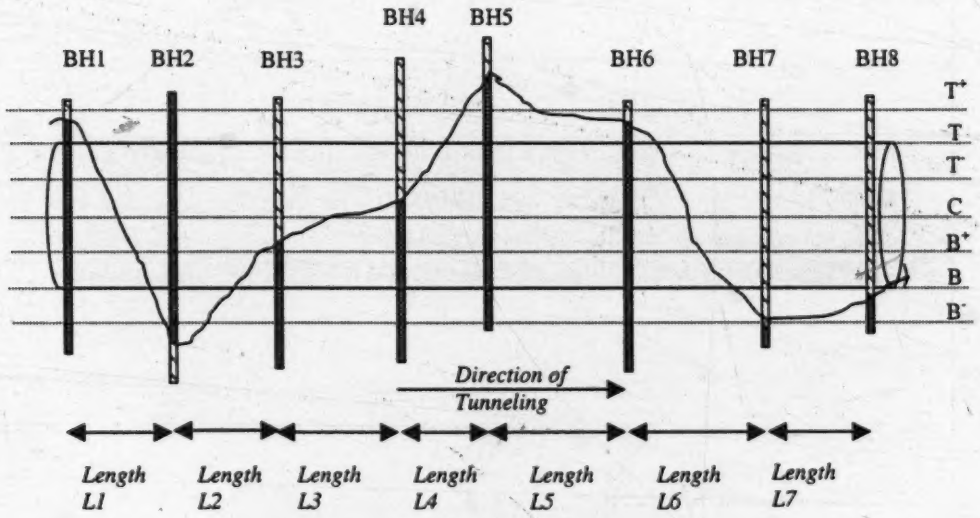


Figure 6-5: Transitions of Soils in the tunnel

Figure 6-5 represents a tunnel with eight boreholes. There are only two soil types in the vicinity of the tunnel. The transitions are enumerated separately in seven elevation levels. The elevation level considers any gradients (if any) in the tunnel from its start to the end. In this study, the observations are made at discrete points along the tunnel as the discrete points represent the boreholes or additional transitional boundary points (based on Chapter 5) provide more deterministic information. However, if the observations can be made at equal intervals, it would provide uniformity in determining transitions. The

following are the elevation levels, which reflect the sample of the soil combinations in the tunnel vicinity.

a) Top of the tunnel elevation (T)

b) Bottom of the tunnel elevation (B)

c) Center of the tunnel elevation (C)

d) Mid point between Top and Center of the tunnel elevation (T^-)

e) Mid point between Center and Bottom of the tunnel elevation (B^+)

f) One point (user-determined) above the Top of the tunnel elevation (T^+)

g) One point (user-determined) below the bottom of the tunnel elevation (B^-)

The (f) and (g) requirements are user inputs. Based on the distribution of the soil profiles between the start and end of the tunnel, the value for (f) and (g) could be determined. In this example, it is limited to one meter just below and above the tunnel to verify that the transitions may consider the possible occurrence of soil types closer to the tunnel's top and bottom elevations. Table 6-2 represents the transitional probabilities of the following combinations for the tunnel depicted in Figure 6-5 based on Equation (6.1). A sample calculation is also given below to explain the calculations of the equation. The transitional probabilities in the matrix are stationary (or homogeneous) for the tunnel as the prediction uses these probabilities throughout the entire tunnel. It represents the probability of moving from one soil to another or remaining in the same soil type.

T^+ = AAAABAAA

T = BAAABBAA

T^- = BBAABBAA

C = BAABBBAA

B^+ = BABBBBAA

B = BABBBBAA

B^- = BBBBBBAB

For example, Elevation T generates all four transitional probabilities. There are 3 transitions from A to A and 1 transition from A to B with a total of 4 transitions generated from A. This prompts the calculation of the transitional probability of A to A as 0.75 (3 out of 4 transitions) and transitional probability of A to B as 0.25 (1 out of 4 transitions). The transition probability of B to A is then 0.67 (2/3 transitions) and B to B is 0.33 (1/3 transitions).

Table 6-2: Transitional Probabilities for the Tunnel in Figure 6-5

	P(A/A)	P(A/B)	P(B/A)	P(B/B)
T+	0.83	0.17	1.00	0.00
T	0.75	0.25	0.67	0.33
T -	0.75	0.25	0.67	0.33
C	0.67	0.33	0.50	0.50
B+	0.50	0.50	0.40	0.60
B	0.50	0.50	0.40	0.60
B -	0.00	1.00	0.17	0.83

Three transition probability matrices are created from the data in Table 6-2: Top Matrix (Table 6-3a) to calculate the transition point at the top elevation; Center matrix (Table 6-3 b) to calculate the transition of soils in the middle of the tunnel, if any; and Bottom matrix (Table 6-3 c) to calculate the transition point at the bottom elevation. Top matrix

obtains the transitions at elevations T^+, T, and T^-, Center matrix obtains the transitions at elevations T^-, C, and B^+ and Bottom matrix obtains the transitions at elevations B^+, B, and B^-.

Table 6-3: Transitional Probability Matrices - Top, Center and Bottom i) Transitional Probabilities ii) Transitions

a) Top

	Soil A	Soil B
Soil A	0.786	0.214
Soil B	0.714	0.286

b) Center

	Soil A	Soil B
Soil A	0.667	0.333
Soil B	0.500	0.500

c) Bottom

	Soil A	Soil B
Soil A	0.400	0.600
Soil B	0.313	0.688

a) Top

	Soil A	Soil B
Soil A	11	3
Soil B	5	2

b) Center

	Soil A	Soil B
Soil A	6	3
Soil B	6	6

c) Bottom

	Soil A	Soil B
Soil A	2	3
Soil B	5	11

The calculation of the transitional probabilities based on Markov theory should adhere to the following additional rules before application, as proposed by many researchers such as Krumbein and Dacey (1969), Scherer (1968) and Schwarzacher (1969).

a) The number of states is finite.

b) There are certain states known as Absorbing states. If a state is not changed, it is called as an absorbing state (for example transiting is only from A to A and never from A to B). However, no absorbing states are allowed in the soil transition methodology, so that $P_{ij} < 1$ for all i and j. P_{T+} (B/A), P_{B+} (A/A), P_B (B/A), and P_{B-} (A/B) are absorbing states. The reason for observing transitional probabilities at assigned elevation levels is to combine them to generate three separate matrices to avoid having absorbing states.

c) Given that any soil state i occurs at location r_n, there is a positive probability that each soil state j may occur at location r_{n+1}, so that $P_{ij} > 0$ for all i and j.

d) The sum of all transitional probabilities commencing from State i *or* j should be equal to 1.

6.3.4 Rules in Transitional Probability Matrices for Soil Prediction (Three Continuous Soils)

The transitional probabilities need to be modified to predict the transition points if there are more than two soils. For example, if there are three soils in the vicinity of the tunnel and the transition is between only two of them at once, the modified transitional probabilities are generated for the two soils involved. Figure 6-6 shows an example of involving three soils. Table 6-4 depicts the transitional probability matrices for top, center, and bottom of soils.

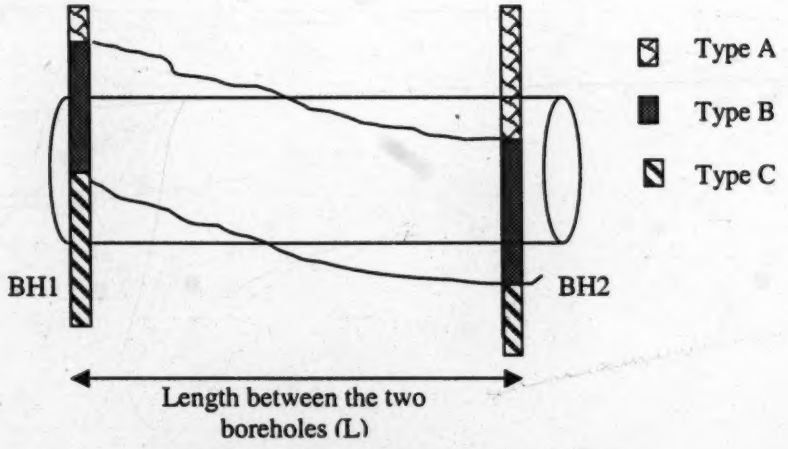


Figure 6-6: Transition of Three Soil Types

Figure 6-6 depicts that the transition from Soil B to Soil A at top, and the transition from Soil C to Soil B at bottom. Modified transition probabilities are created only for the purpose of calculating the transition points for two soils, ignoring the third soil. For example, the transitional probability at bottom from Soil C to Soil B is only 3 transitions out of 5, giving a modified probability of 0.60 rather than obtaining 0.300 as in Table 6-4. The modified transitional probability for Soil B to A in the top matrix is 6 of 10, which is 0.60 rather than the table's value of 0.462, to calculate the transition points along the tunnel.

Table 6-4: Transitional Matrices for 3 soils

a) Top

	Soil A	Soil B	Soil C
Soil A	7	4	2
Soil B	6	4	3
Soil C	5	3	2

b) Center

	Soil A	Soil B	Soil C
Soil A	4	2	4
Soil B	5	9	2
Soil C	3	3	4

c) Bottom

	Soil A	Soil B	Soil C
Soil A	2	1	4
Soil B	5	12	2
Soil C	2	3	6

a) Top

	Soil A	Soil B	Soil C
Soil A	0.538	0.308	0.154
Soil B	0.462	0.308	0.231
Soil C	0.500	0.300	0.200

b) Center

	Soil A	Soil B	Soil C
Soil A	0.400	0.200	0.400
Soil B	0.313	0.563	0.125
Soil C	0.300	0.300	0.400

c) Bottom

	Soil A	Soil B	Soil C
Soil A	0.286	0.143	0.571
Soil B	0.263	0.632	0.105
Soil C	0.200	0.300	0.500

6.4 Modeling Algorithms Based on the Transition Scenarios of the Soils

There are several combinations (families) of soils that make up the stratigrahy of any area. Chapter 5 explains the various families of soils in Edmonton stratigraphy. The representation of those soils also has numerous variations. For example, Figure 6-4 shows

five different combinations of soils with only two soil types in the tunnel area. The modeling algorithms for identifying the transitions of soils vary according to the following factors:

a) Number of soils in the area

b) Start and end elevations of the soils

c) Direction of the soil profiles

d) Status of the soil types (continuous or pockets)

e) Start and end elevation of the tunnel between boreholes.

The various combinations of two continuous layer soils, which are used to model for simulation purposes, are in Table 6-5. Table 6-6 provides the combinations of one continuous soil layer with the other soil as a pocket. The following are the five combinations of continuous soils depicted through the example tunnel in Figure 6-4.

1. Transition of one soil to another (Soil B to Soil A) both at top of the tunnel and bottom of the tunnel (for example, BH1 to BH2 and BH6 to BH7). This requires predicting the transition point both at top and bottom elevations of the tunnel.
2. Transition of Soil A to Soil B only occurs at the top (BH4 and BH5) requiring the prediction of the top transition point.
3. Transition of Soil A to Soil B only occurs at the bottom (BH2 and BH3) requiring the prediction of the bottom transition point.
4. There is no transition of soil types either at the top or bottom of the tunnel. Transition only occurs between the top and bottom elevations of the tunnel (BH3 and BH4) requiring no prediction of transition points at the top and bottom of the tunnel.

5. There is no transition of soil types at top, bottom or inside of the tunnel. Transition only occurs above or below the tunnel (BH5 to BH6 and BH7 and BH8) requiring no prediction of transition point at top and bottom of the tunnel.

Figure 6-7 (a modified version of Figure 6-1), is used to illustrate the modeling algorithms of Scenario # 1 in Table 6-5. The modeling algorithm for each scenario comprises three stages: calculation of the transition point, composition of soils, and rate of boring.

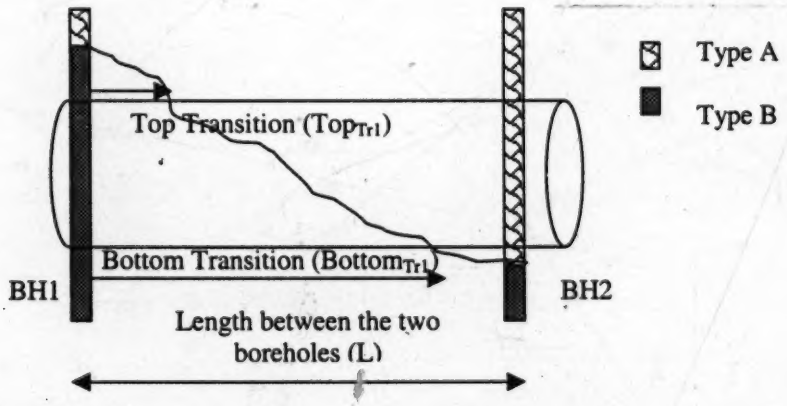


Figure 6-7: Transition of Soils – Two soils both at Top and Bottom Elevations

Although some of the scenarios in Table 6.5 are very similar in terms of the transitions at top and bottom, the location of the transition point could make a difference in determining the rate of boring for productivity. The complete algorithm for Scenario # 1 is given in Section 6.4.1. Scenario #1 comprises the transition of Soil B to Soil A both at top and bottom elevation of the tunnel.

Table 6-5: Combinations of two continuous soil layers

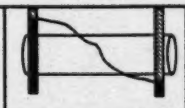
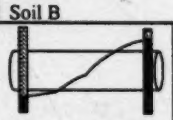
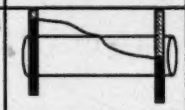
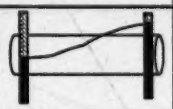
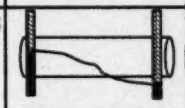
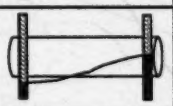
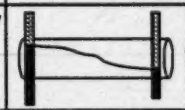
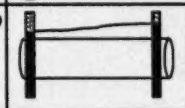
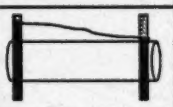
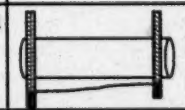
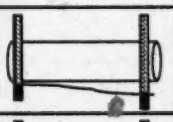
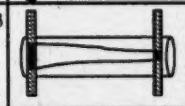
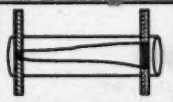
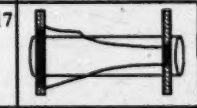
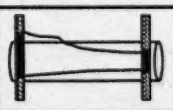
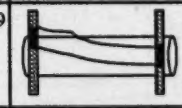
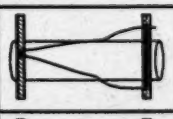
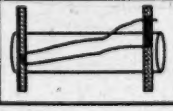
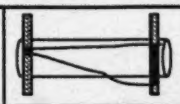
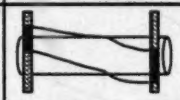
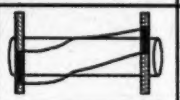
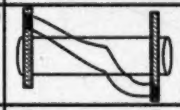
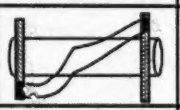
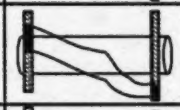
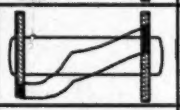
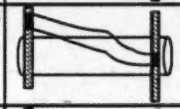
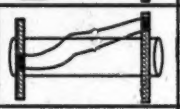
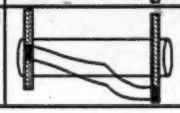
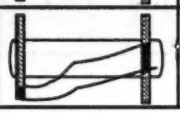
No	Scenario	Transitions	No	Scenario	Transitions
	Soil A		Soil B		
1		Top (B to A) Bottom (B to A)	2		Top (A to B) Bottom (A to B)
3		Top (B to A) Bottom (None)	4		Top (A to B) Bottom (None)
5		Top (None) Bottom (B to A)	6		Top (None) Bottom (A to B)
7		Top (None) Bottom (None)	8		Top (None) Bottom (None)
9		Top (None) Bottom (None)	10		Top (None) Bottom (None)
11		Top (None) Bottom (None)	12		Top (None) Bottom (None)
13		Top (None) Bottom (None)	14		Top (None) Bottom (None)
15		Top (None) Bottom (None)	16		Top (None) Bottom (None)
17		Top (B to A) Bottom (B to A)	18		Top (B to A) Bottom (None)
19		Top (B to A) Bottom (None)	20		Top (A to B) Bottom (A to B)
21		Top (None) Bottom (B to A)	22		Top (None) Bottom (B to A)
23		Top (A to B) Bottom (None)	24		Top (A to B) Bottom (None)

Table 6-5: Combinations of two continuous soil layers (Cont.)

No	Scenario	Transitions	No	Scenario	Transitions
	Soil A Soil B				
25		Top (None) Bottom (A to B)	26		Top (None) Bottom (A to B)
27		Top (B to A) Bottom (A to B)	28		Top (A to B) Bottom (B to A)
29		Top (A to B & B to A) Bottom (A to B & B to A)	30		Top (A to B & B to A) Bottom (A to B & B to A)
31		Top (B to A) Bottom (A to B & B to A)	32		Top (A to B) Bottom (A to B & B to A)
33		Top (A to B & B to A) Bottom (None)	34		Top (A to B & B to A) Bottom (None)
35		Top (None) Bottom (A to B & B to A)	36		Top (None) Bottom (A to B & B to A)

6.4.1 Calculation of Transition Points – Scenario # 1

a) Generate random numbers between 0 and 1 equal to the length between the two boreholes (generate L times random numbers)

b) Arrange the random numbers in descending order with an assigned index number for each random number.

c) Use the following algorithm to determine whether the random number belongs to soil A or soil B. This algorithm is a modified version from Wales (1994) to calculate the transition points. If the transition is from Soil B to A, the transitional probability of $P_{Top}(B/A)$ is the decision making threshold value. If the transition is from Soil A to B, the transitional probability of $P_{Top}(A/B)$ is the decision-making threshold value.

Random Number <= $P_{Top}(B/A)$ ⟶ *Soil A*.....*(6.3)*

Random Number > P_{Top} *(B/A)* ⟶ *Soil B*.....*(6.4)*

d) Identify the index number, which changes from Soil B to A. This index number is the top transition length (Top_{Trl}) from Borehole BH1.

e) Re-generate random numbers between 0 and 1 equal to the distance between top transition point and BH2 (L - Top_{Trl}). Since the top transition and bottom transition are generated from the same profile, the distance is obtained between the top transition point and the BH2.

f) Arrange the random numbers in descending order with an assigned index number for each random number.

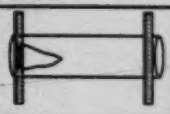
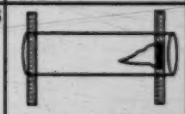
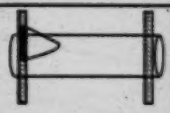
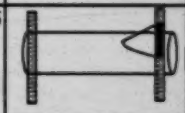
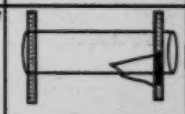
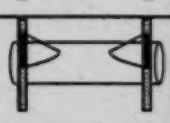
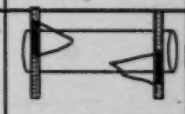
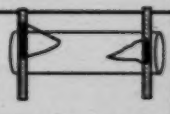
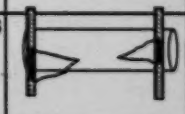
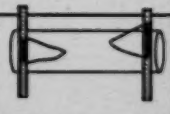
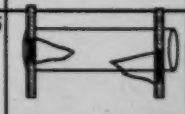
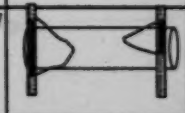
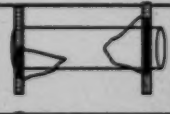
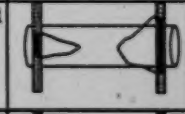
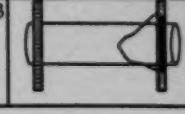
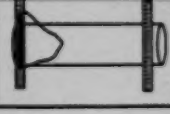
g) Use the same algorithm to determine whether the random number belongs to soil A or soil B.

Random Number <= $P_{Bottom}(B/A)$ ⟶ *Soil A*.....*(6.5)*

Random Number > P_{Bottom} *(B/A)* ⟶ *Soil B*.....*(6.6)*

h) Identify the index number, which changes from Soil B to A. The index number is the bottom transition point from the top transition point.

Table 6-6: Combinations of Continuous Soil Layers and Soil Pockets

No	Scenario	Transitions	No	Scenario	Transitions
		Soil A Soil B			
101		Top (None) Center Left (B to A) Center Right (A to B) Bottom (None)	102		Top (None) Center Left (B to A) Center Right (None) Bottom (None)
103		Top (None) Center Left (None) Center Right (A to B) Bottom (None)	104		Top (B to A) Center Left (B to A) Center Right (None) Bottom (None)
105		Top (A to B) Center Left (None) Center Right (A to B) Bottom (None)	106		Top (None) Center Left (B to A) Center Right (None) Bottom (B to A)
107		Top (None) Center Left (None) Center Right (A to B) Bottom (A to B)	108		Top (B to A) & (A to B) Center Left (B to A) Center Right (A to B) Bottom (None)
109		Top (None) Center Left (B to A) Center Right (A to B) Bottom (B to A) & (A to B)	110		Top (A to B) Center Left (B to A) Center Right (A to B) Bottom (B to A)
111		Top (B to A) Center Left (B to A) Center Right (A to B) Bottom (A to B)	112		Top (B to A) Center Left (B to A) Center Right (A to B) Bottom (None)
113		Top (None) Center Left (B to A) Center Right (A to B) Bottom (B to A)	114		Top (A to B) Center Left (B to A) Center Right (A to B) Bottom (None)
115		Top (None) Center Left (B to A) Center Right (A to B) Bottom (A to B)	116		Top (B to A) Center Left (B to A) Center Right (A to B) Bottom (B to A)
117		Top (B to A) & (A to B) Center Left (B to A) Center Right (A to B) Bottom (B to A)	118		Top (B to A) Center Left (B to A) Center Right (A to B) Bottom (B to A) & (A to B)
119		Top (B to A) & (A to B) Center Left (B to A) Center Right (A to B) Bottom (A to B)	120		Top (A to B) Center Left (B to A) Center Right (A to B) Bottom (B to A) & (A to B)
121		Top (A to B) Center Left (B to A) Center Right (A to B) Bottom (A to B)	122		Top (B to A) & (A to B) Center Left (B to A) Center Right (A to B) Bottom (B to A) & (A to B)
123		Top (A to B) Center Left (None) Center Right (A to B) Bottom (A to B)	124		Top (B to A) Center Left (B to A) Center Right (None) Bottom (B to A)

6.4.2 Calculation of the Composition of Soil and the profile of the Transition Curve – Scenario # 1

Calculation of the composition of soil is essential in calculating the volume bored, which eventually determines the travel times of the trains and the duration of the dirt removal process in tunnel operations. Further, the composition of the soil could be used to determine the boring rate, as described in the section 6.4.3.

a) Between BH1 and top transition point: Only soil B is found in this portion.

Composition of Soil B $= 1$ .....(6.7)

Composition of Soil A $= 0$ .....(6.8)

b) Between top transition point and bottom transition point:

i. Generate random numbers from 0 to 1 equal to the distance (Top_{Trl} and $Bottom_{Trl}$)

ii. Arrange them in descending order with an assigned index number ($i = 1$ to ($Bottom_{Trl} - Top_{Trl}$)) for each random number

iii. Calculate the composition using the formula

Composition at Point i for Soil B= Sorted Random Number i .....(6.9)

Composition at Point i for Soil A = (1 - Sorted Random Number i).....(6.10)

c) Between bottom transition Point and BH2: Only soil A is found in this portion.

Composition of Soil A $= 1$ .....(6.11)

Composition of Soil B $= 0$ .....(6.12)

6.4.3 Calculation of Boring Rate

Calculation of boring rate depends on various factors, as shown in Figure 4.10. It was found during the research interviews with tunnel personnel at the City of Edmonton that the boring rate in combined soils (mixed combinations of soils) was variable depending of the type of the soil and its inherent properties. The following are the most likely calculation options identified to calculate the boring rate when a new soil is found during tunnel excavation in another soil:

a) Boring rate (BR) is a combination of the composition of the soil types.

$$BR = BR_A \times Composition\ of\ Soil\ A + BR_B \times Composition\ of\ Soil\ B \quad ...(6.13)$$

b) Minimum BR value of the two soils

c) Worse than the minimum BR value (BR_{Min}) of the two soils: This was identified as the most common situation by tunnel personnel, although the City of Edmonton cannot justify it with supporting data.

Figure 6-8 shows an example of the combinations of Soil A and Soil B and the section of the soil profiles if the length between the two boreholes is 100 m long and the tunnel depth is 2.54 meters (the typical excavation depth for tunneling using a 2.3-meter diameter TBM). The transition point at the top of the tunnel is 31 meters from BH1 and transition point at the bottom of the tunnel is 14 meters from BH2. Based on the Equations 6.6 and 6.7, the composition of soil B is 1 before the top transition point. Based on Equations 6.10 and 6.11, the composition of Soil A is 1 between the bottom transition point and the second borehole. The section between top transition and the bottom transition are based on Equations 6.8 and 6.9.

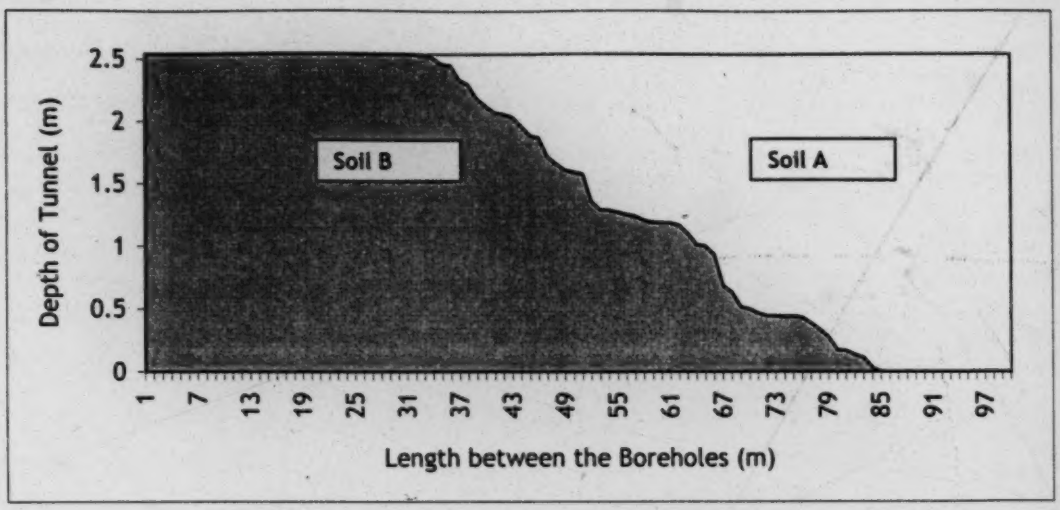


Figure 6-8: Soil Profiles of A and B inside the tunnel depth

6.4.4 Rules of Transition Algorithm Modules for Two Continuous Soil Layers

Algorithms to calculate the transition points for two continuous soil layers vary according to many factors in addition to transitional probability values. The additional factors are the direction of the transition soil profile, number of top transitions, and number of bottom transitions. Figure 6-9 divides the 24 scenarios in Table 6-5 into 9 algorithms modules. Each algorithm module is illustrated in Figure 6-10.

There are various rules that govern if more than one transition point exists either at the top or bottom of the tunnel. For example, if there are 2 transition points at top (scenarios 29, 30, 33, and 34), a second transition point is sampled (using Equations 6.3 and 6.4) between the first top transition and the second borehole (Rule A). The same rule applies when there are two bottom transition (scenarios 29, 30, 31, 32, 35, and 36) points. However, if there is only one top transition point and one only bottom transition point generated from the same profile (Scenarios 1 and 2), the second transition point (bottom)

is sampled between the first top transition and the second borehole (Rule B). However, if there are two top transitions and one bottom transition with the bottom transition generated from one of the profiles from the top transitions (scenarios 31 and 32), Rule A has priority over Rule B.

The algorithms vary slightly within the same module due to the direction of the profiles. All illustrations in Figure 6-10 assume that the soil profiles direction is down. Figure 6-11 shows the modeling algorithm module 2C6 for both directions up and down.

6.4.5 Transition Algorithm Modules for Other Combinations

The following section explains the transition modeling algorithm modules of other scenarios.

a) Two soil types with one of the soils as an intermediate layer inside the main layer. Chapter 5 revealed that there are certain families of soils in this category. For example soil families 85651, 5651, and 75351 have an intermediate layer (Soil 6 within Soil 5, and Soil 3 within Soil 5) which could be continuous across several boreholes or just a pocket in-between two boreholes. The algorithm for Figure 6-12 (continuous) is based on module 2C8 of Figure 6-10. Sample algorithms for a pocket of intermediate soil layer in the boreholes (Figure 6-13 and scenario 111 in Table 6-5) are explained in Appendix "D".

b) Within the thickness of the utility tunnels, it could be possible to find more than two soil types. Hence, the modeling algorithms for a typical situation involving three soils are explained in Appendix "D". Figure 6-14 shows a three-layer case comprising the continuous layers of three separate soils (for families like 7561, 8561, and 8531).

Figure 6.15 shows another scenario comprising two continuous layers and a pocket inside one of the continuous layers (Figure 6-15).

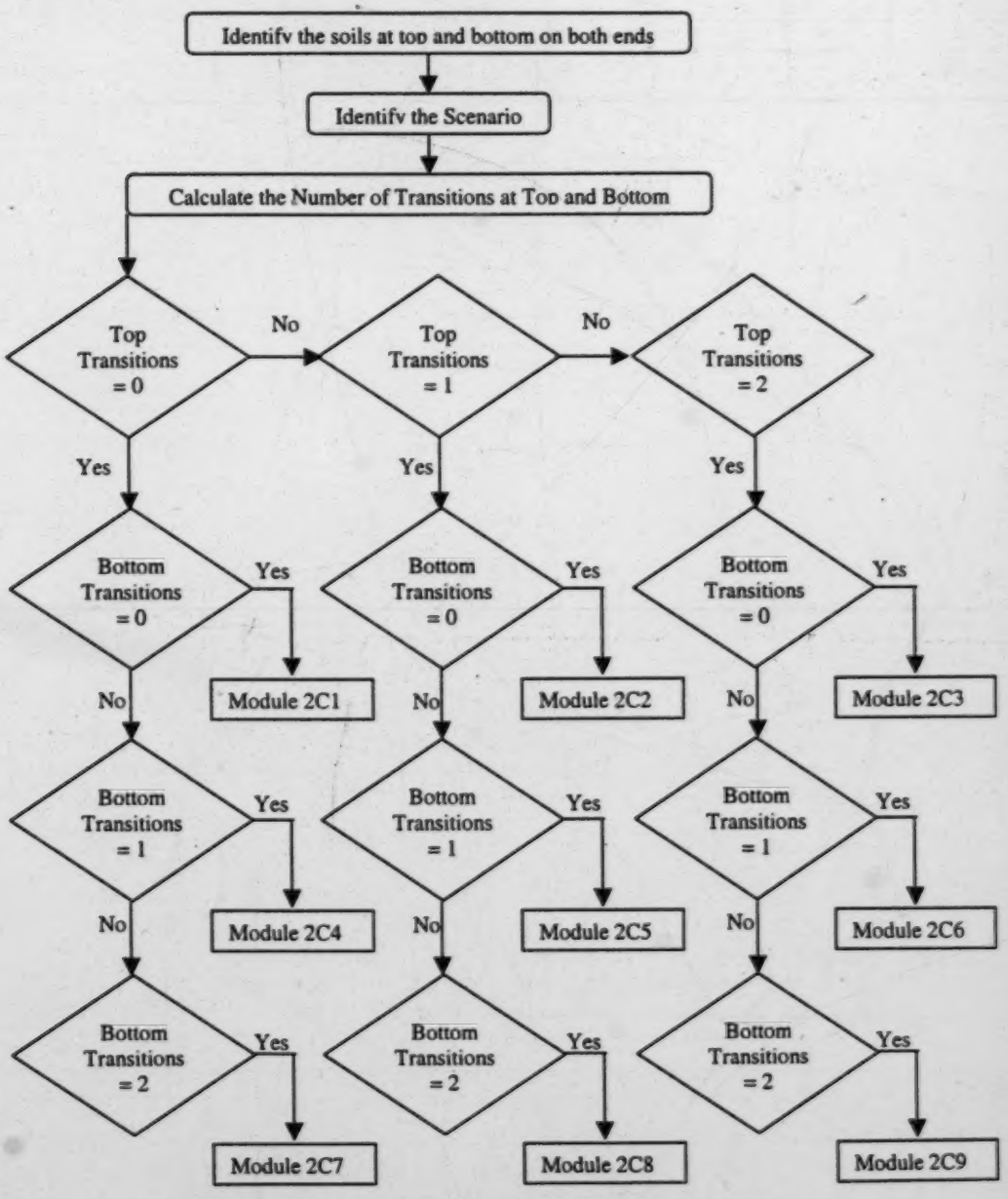


Figure 6-9: Algorithm Modules for Two Continuous Soils

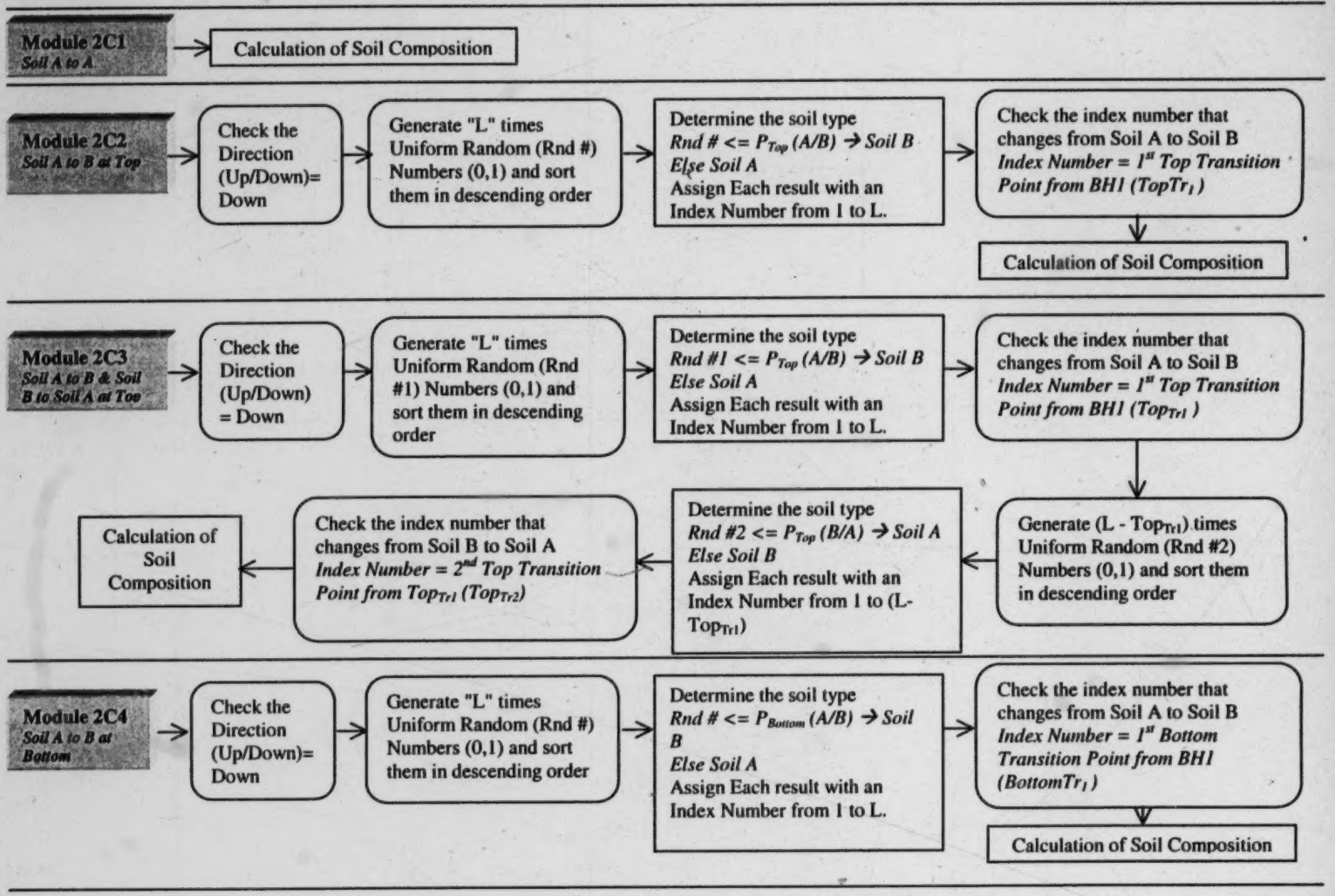

Module 2C1
Soil A to A
Calculation of Soil Composition
Module 2C2
Soil A to B at Top
Check the Direction (Up/Down)= Down
Generate "L" times Uniform Random (Rnd #) Numbers (0,1) and sort them in descending order
Determine the soil type
Rnd # <= P_{Top} (A/B) → Soil B
Else Soil A
Assign Each result with an Index Number from 1 to L.
Check the index number that changes from Soil A to Soil B
Index Number = 1st Top Transition Point from BH1 ($TopTr_1$)
Calculation of Soil Composition
Module 2C3
Soil A to B & Soil B to Soil A at Toe
Check the Direction (Up/Down) = Down
Generate "L" times Uniform Random (Rnd #1) Numbers (0,1) and sort them in descending order
Determine the soil type
Rnd #1 <= P_{Top} (A/B) → Soil B
Else Soil A
Assign Each result with an Index Number from 1 to L.
Check the index number that changes from Soil A to Soil B
Index Number = 1st Top Transition Point from BH1 (Top_{Tr1})
Generate (L - Top_{Tr1}) times Uniform Random (Rnd #2) Numbers (0,1) and sort them in descending order
Determine the soil type
Rnd #2 <= P_{Top} (B/A) → Soil A
Else Soil B
Assign Each result with an Index Number from 1 to (L-Top_{Tr1})
Check the index number that changes from Soil B to Soil A
Index Number = 2nd Top Transition Point from Top_{Tr1} (Top_{Tr2})
Calculation of Soil Composition
Module 2C4
Soil A to B at Bottom
Check the Direction (Up/Down)= Down
Generate "L" times Uniform Random (Rnd #) Numbers (0,1) and sort them in descending order
Determine the soil type
Rnd # <= P_{Bottom} (A/B) → Soil B
Else Soil A
Assign Each result with an Index Number from 1 to L.
Check the index number that changes from Soil A to Soil B
Index Number = 1st Bottom Transition Point from BH1 ($BottomTr_1$)
Calculation of Soil Composition

Figure 6-10: Algorithm Modules for Scenarios stated in Table 6-5

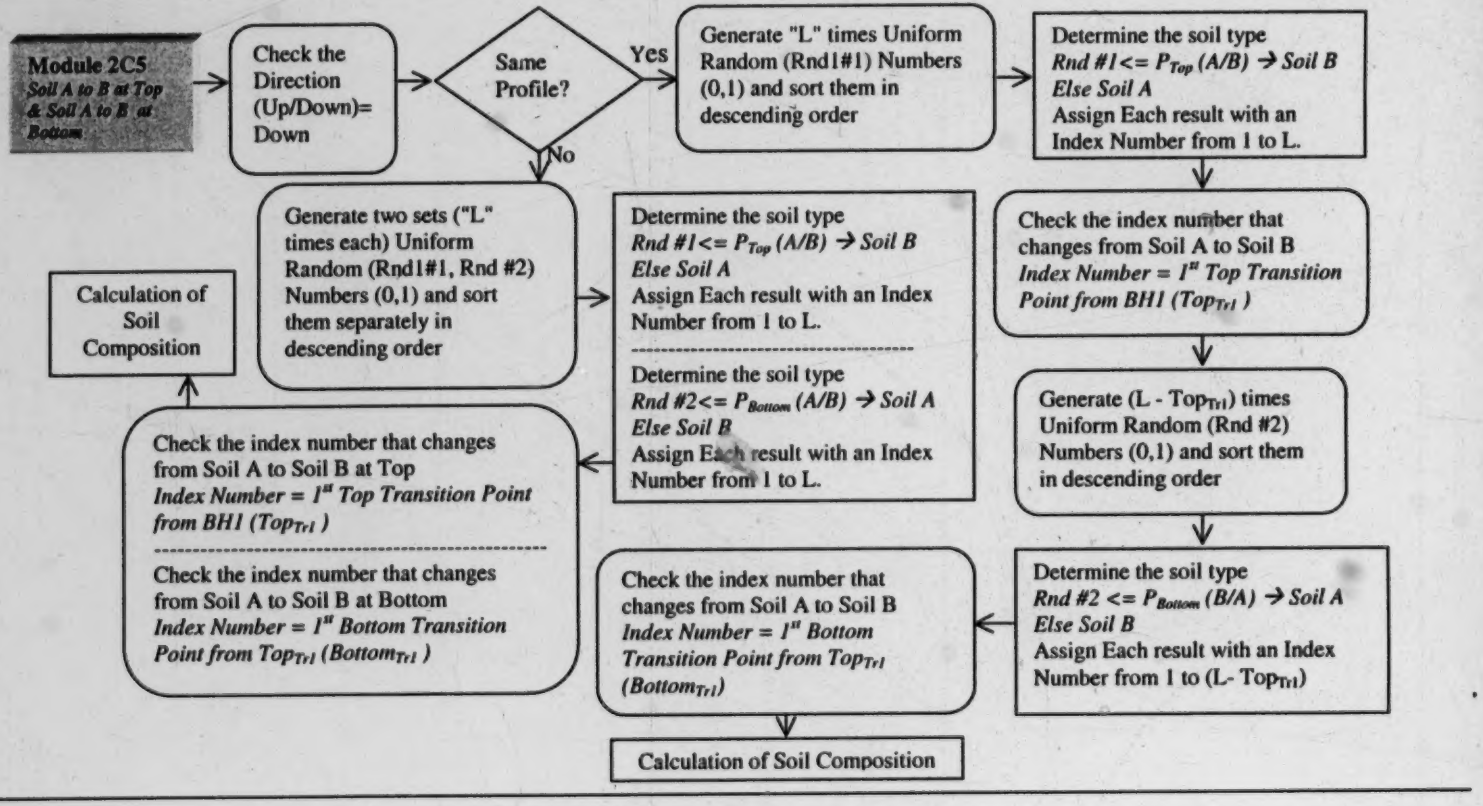

Module 2C5
Soil A to B at Top & Soil A to B at Bottom
Check the Direction (Up/Down)= Down
Same Profile?
Yes
No
Generate "L" times Uniform Random (Rnd1#1) Numbers (0,1) and sort them in descending order
Determine the soil type
Rnd #1<= P_Top (A/B) → Soil B
Else Soil A
Assign Each result with an Index Number from 1 to L.
Check the index number that changes from Soil A to Soil B
Index Number = 1st Top Transition Point from BH1 (Top_Tr1)
Generate (L - Top_Tr1) times Uniform Random (Rnd #2) Numbers (0,1) and sort them in descending order
Determine the soil type
Rnd #2 <= P_Bottom (B/A) → Soil A
Else Soil B
Assign Each result with an Index Number from 1 to (L- Top_Tr1)
Check the index number that changes from Soil A to Soil B
Index Number = 1st Bottom Transition Point from Top_Tr1 (Bottom_Tr1)
Calculation of Soil Composition
Generate two sets ("L" times each) Uniform Random (Rnd1#1, Rnd #2) Numbers (0,1) and sort them separately in descending order
Determine the soil type
Rnd #1<= P_Top (A/B) → Soil B
Else Soil A
Assign Each result with an Index Number from 1 to L.
Determine the soil type
Rnd #2<= P_Bottom (A/B) → Soil A
Else Soil B
Assign Each result with an Index Number from 1 to L.
Check the index number that changes from Soil A to Soil B at Top
Index Number = 1st Top Transition Point from BH1 (Top_Tr1)
Check the index number that changes from Soil A to Soil B at Bottom
Index Number = 1st Bottom Transition Point from Top_Tr1 (Bottom_Tr1)
Calculation of Soil Composition

Figure 6-10: Algorithm Modules for Scenarios stated in Table 6-5

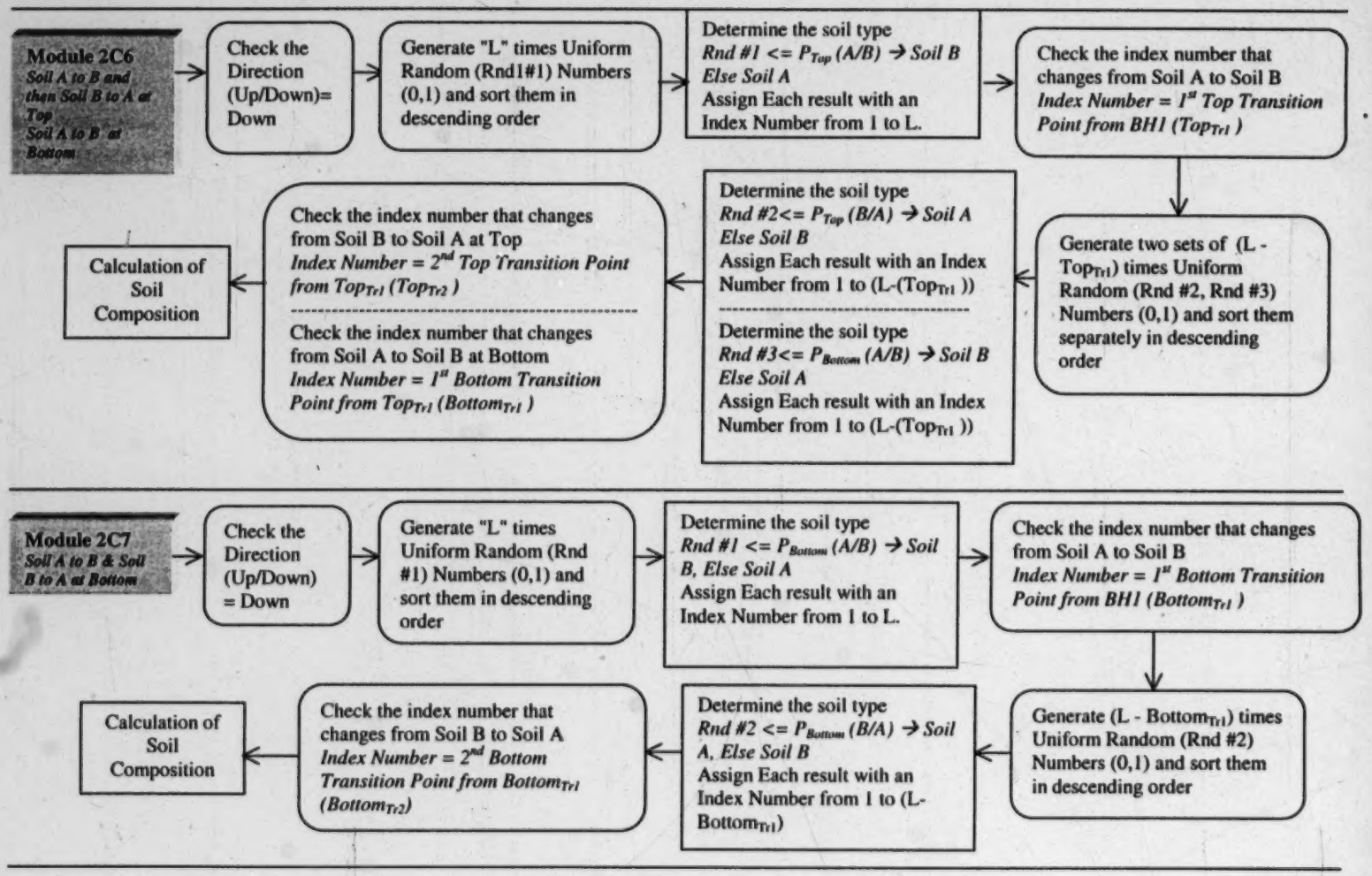

Module 2C6
Soil A to B and then Soil B to A at Top
Soil A to B at Bottom
Check the Direction (Up/Down)= Down
Generate "L" times Uniform Random (Rnd1#1) Numbers (0,1) and sort them in descending order
Determine the soil type
Rnd #1 <= P_{Top} (A/B) → Soil B
Else Soil A
Assign Each result with an Index Number from 1 to L.
Check the index number that changes from Soil A to Soil B
Index Number = 1st Top Transition Point from BH1 (Top_{Tr1})
Generate two sets of (L - Top_{Tr1}) times Uniform Random (Rnd #2, Rnd #3) Numbers (0,1) and sort them separately in descending order
Determine the soil type
Rnd #2<= P_{Top} (B/A) → Soil A
Else Soil B
Assign Each result with an Index Number from 1 to (L-(Top_{Tr1}))
Determine the soil type
Rnd #3<= P_{Bottom} (A/B) → Soil B
Else Soil A
Assign Each result with an Index Number from 1 to (L-(Top_{Tr1}))
Check the index number that changes from Soil B to Soil A at Top
Index Number = 2nd Top Transition Point from Top_{Tr1} (Top_{Tr2})
Check the index number that changes from Soil A to Soil B at Bottom
Index Number = 1st Bottom Transition Point from Top_{Tr1} ($Bottom_{Tr1}$)
Calculation of Soil Composition
Module 2C7
Soil A to B & Soil B to A at Bottom
Check the Direction (Up/Down) = Down
Generate "L" times Uniform Random (Rnd #1) Numbers (0,1) and sort them in descending order
Determine the soil type
Rnd #1 <= P_{Bottom} (A/B) → Soil B, Else Soil A
Assign Each result with an Index Number from 1 to L.
Check the index number that changes from Soil A to Soil B
Index Number = 1st Bottom Transition Point from BH1 ($Bottom_{Tr1}$)
Generate (L - $Bottom_{Tr1}$) times Uniform Random (Rnd #2) Numbers (0,1) and sort them in descending order
Determine the soil type
Rnd #2 <= P_{Bottom} (B/A) → Soil A, Else Soil B
Assign Each result with an Index Number from 1 to (L-$Bottom_{Tr1}$)
Check the index number that changes from Soil B to Soil A
Index Number = 2nd Bottom Transition Point from $Bottom_{Tr1}$ ($Bottom_{Tr2}$)
Calculation of Soil Composition

Figure 6-10: Algorithm Modules for Scenarios stated in Table 6-5

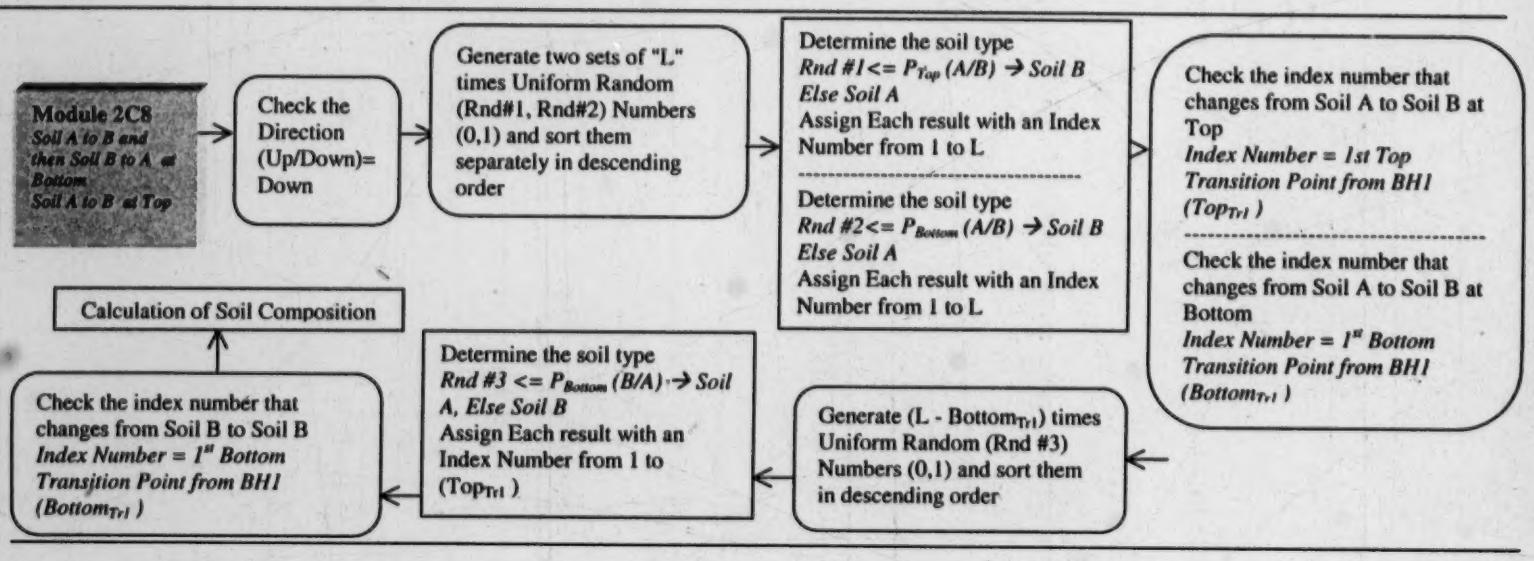

Module 2C8
Soil A to B and then Soil B to A at Bottom
Soil A to B at Top
Check the Direction (Up/Down)= Down
Generate two sets of "L" times Uniform Random (Rnd#1, Rnd#2) Numbers (0,1) and sort them separately in descending order
Determine the soil type
Rnd #1<= P_{Top} (A/B) → Soil B Else Soil A
Assign Each result with an Index Number from 1 to L
Determine the soil type
Rnd #2<= P_{Bottom} (A/B) → Soil B Else Soil A
Assign Each result with an Index Number from 1 to L
Check the index number that changes from Soil A to Soil B at Top
Index Number = 1st Top Transition Point from BH1 (Top_{Tr1})
Check the index number that changes from Soil A to Soil B at Bottom
Index Number = 1st Bottom Transition Point from BH1 ($Bottom_{Tr1}$)
Generate (L - $Bottom_{Tr1}$) times Uniform Random (Rnd #3) Numbers (0,1) and sort them in descending order
Determine the soil type
Rnd #3 <= P_{Bottom} (B/A) → Soil A, Else Soil B
Assign Each result with an Index Number from 1 to (Top_{Tr1})
Check the index number that changes from Soil B to Soil B
Index Number = 1st Bottom Transition Point from BH1 ($Bottom_{Tr1}$)
Calculation of Soil Composition

Figure 6-10: Algorithm Modules for Scenarios stated in Table 6-5

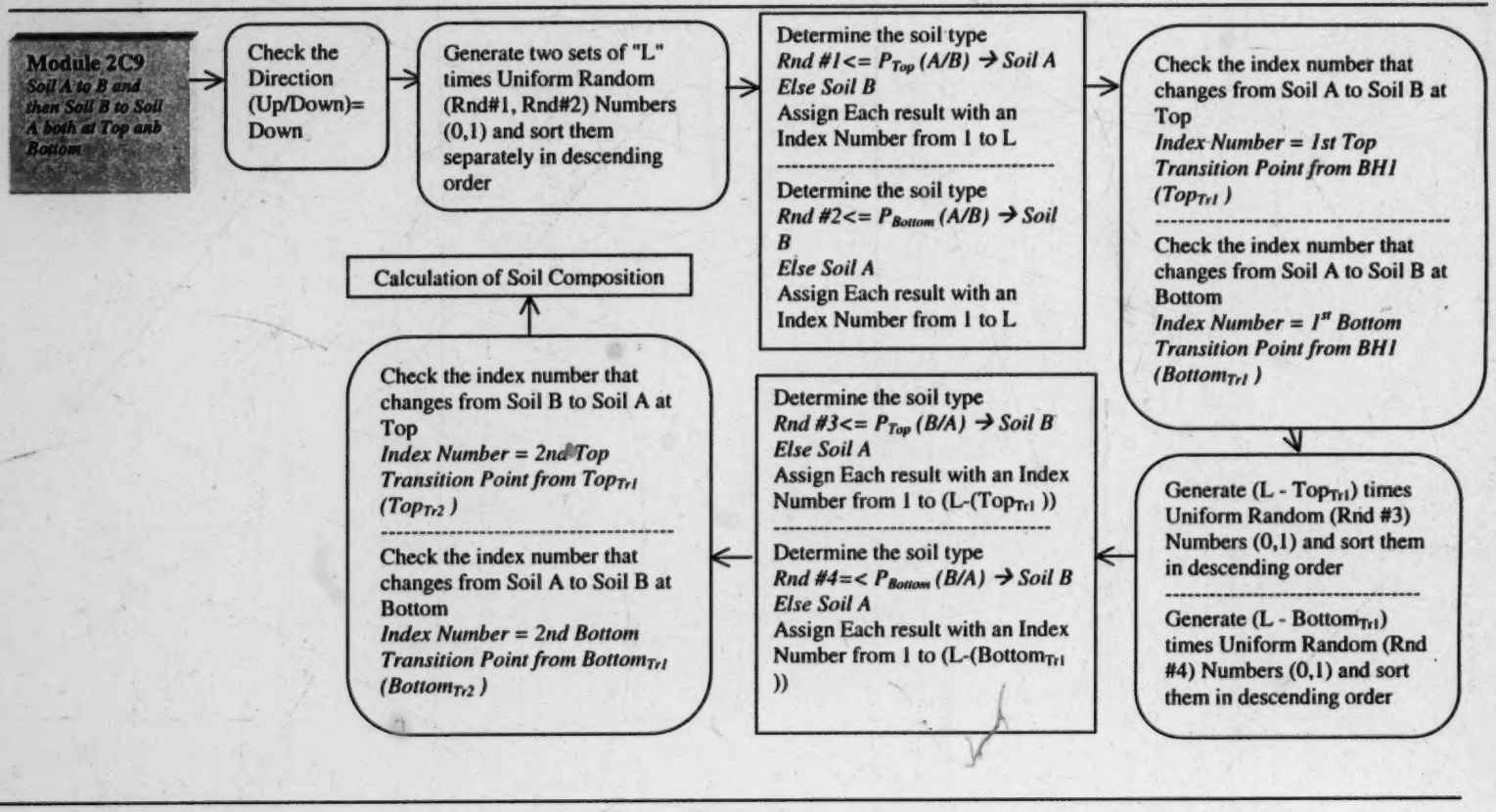

Module 2C9
Soil A to B and then Soil B to Soil A both at Top and Bottom
Check the Direction (Up/Down)= Down
Generate two sets of "L" times Uniform Random (Rnd#1, Rnd#2) Numbers (0,1) and sort them separately in descending order
Determine the soil type
Rnd #1<= P_{Top} (A/B) → Soil A
Else Soil B
Assign Each result with an Index Number from 1 to L
Determine the soil type
Rnd #2<= P_{Bottom} (A/B) → Soil B
Else Soil A
Assign Each result with an Index Number from 1 to L
Check the index number that changes from Soil A to Soil B at Top
Index Number = 1st Top Transition Point from BH1 (Top_{Tr1})
Check the index number that changes from Soil A to Soil B at Bottom
Index Number = 1st Bottom Transition Point from BH1 ($Bottom_{Tr1}$)
Generate (L - Top_{Tr1}) times Uniform Random (Rnd #3) Numbers (0,1) and sort them in descending order
Generate (L - $Bottom_{Tr1}$) times Uniform Random (Rnd #4) Numbers (0,1) and sort them in descending order
Determine the soil type
Rnd #3<= P_{Top} (B/A) → Soil B
Else Soil A
Assign Each result with an Index Number from 1 to (L-(Top_{Tr1}))
Determine the soil type
Rnd #4=< P_{Bottom} (B/A) → Soil B
Else Soil A
Assign Each result with an Index Number from 1 to (L-($Bottom_{Tr1}$))
Check the index number that changes from Soil B to Soil A at Top
Index Number = 2nd Top Transition Point from Top_{Tr1} (Top_{Tr2})
Check the index number that changes from Soil A to Soil B at Bottom
Index Number = 2nd Bottom Transition Point from $Bottom_{Tr1}$ ($Bottom_{Tr2}$)
Calculation of Soil Composition

Figure 6-10: Algorithm Modules for Scenarios stated in Table 6-5

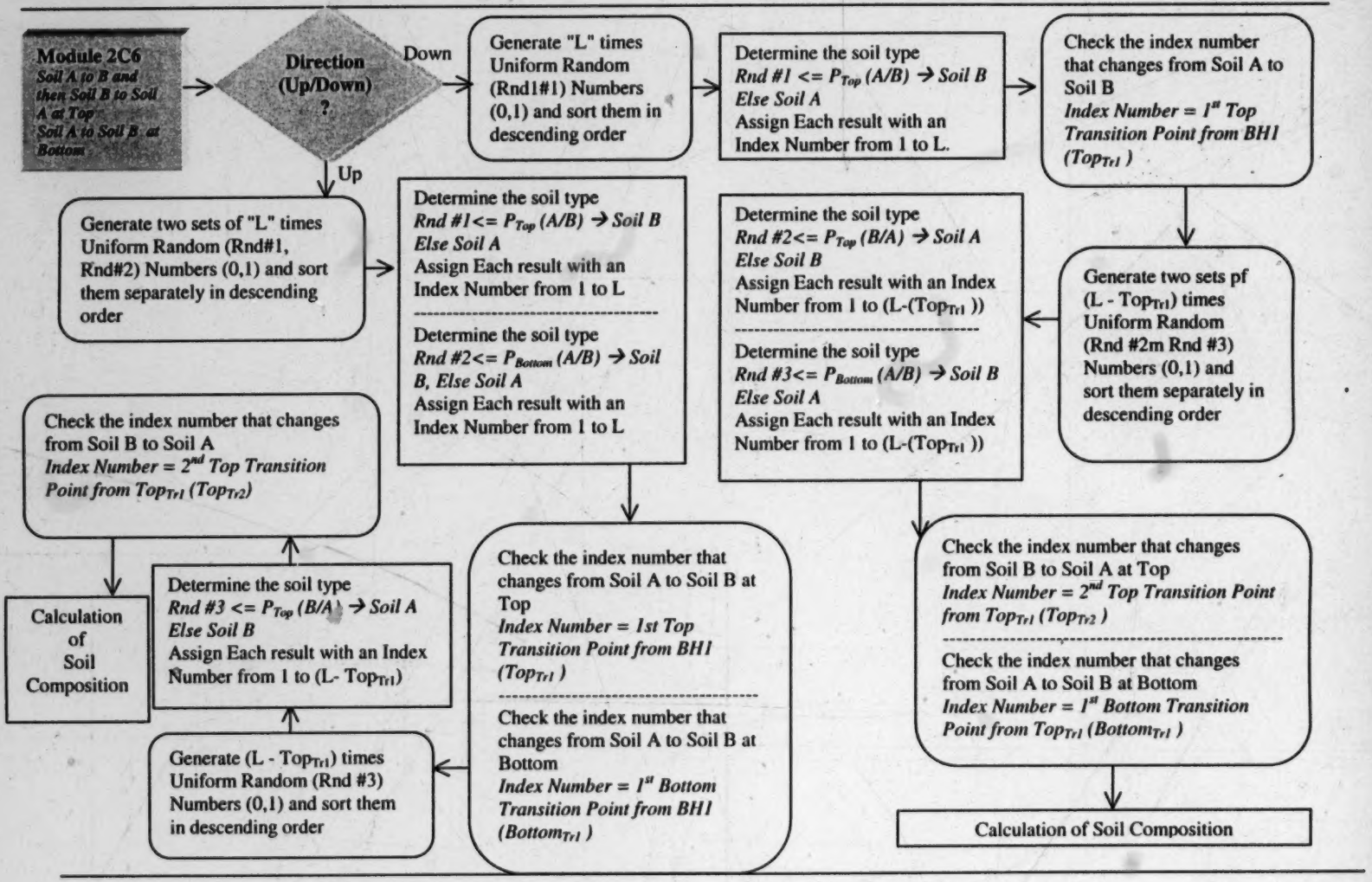

Module 2C6
Soil A to B and then Soil B to Soil A at Top
Soil A to Soil B at Bottom
Direction (Up/Down) ?
Down
Up
Generate "L" times Uniform Random (Rnd1#1) Numbers (0,1) and sort them in descending order
Determine the soil type
Rnd #1 <= P_{Top} (A/B) → Soil B
Else Soil A
Assign Each result with an Index Number from 1 to L.
Check the index number that changes from Soil A to Soil B
Index Number = 1st Top Transition Point from BH1 (Top_{Tr1})
Generate two sets of "L" times Uniform Random (Rnd#1, Rnd#2) Numbers (0,1) and sort them separately in descending order
Determine the soil type
Rnd #1<= P_{Top} (A/B) → Soil B
Else Soil A
Assign Each result with an Index Number from 1 to L
Determine the soil type
Rnd #2<= P_{Bottom} (A/B) → Soil B, Else Soil A
Assign Each result with an Index Number from 1 to L
Determine the soil type
Rnd #2<= P_{Top} (B/A) → Soil A
Else Soil B
Assign Each result with an Index Number from 1 to (L-(Top_{Tr1}))
Determine the soil type
Rnd #3<= P_{Bottom} (A/B) → Soil B
Else Soil A
Assign Each result with an Index Number from 1 to (L-(Top_{Tr1}))
Generate two sets pf ($L - Top_{Tr1}$) times Uniform Random (Rnd #2m Rnd #3) Numbers (0,1) and sort them separately in descending order
Check the index number that changes from Soil B to Soil A
Index Number = 2nd Top Transition Point from Top_{Tr1} (Top_{Tr2})
Calculation of Soil Composition
Determine the soil type
Rnd #3 <= P_{Top} (B/A) → Soil A
Else Soil B
Assign Each result with an Index Number from 1 to ($L - Top_{Tr1}$)
Generate ($L - Top_{Tr1}$) times Uniform Random (Rnd #3) Numbers (0,1) and sort them in descending order
Check the index number that changes from Soil A to Soil B at Top
Index Number = 1st Top Transition Point from BH1 (Top_{Tr1})
Check the index number that changes from Soil A to Soil B at Bottom
Index Number = 1st Bottom Transition Point from BH1 ($Bottom_{Tr1}$)
Check the index number that changes from Soil B to Soil A at Top
Index Number = 2nd Top Transition Point from Top_{Tr1} (Top_{Tr2})
Check the index number that changes from Soil A to Soil B at Bottom
Index Number = 1st Bottom Transition Point from Top_{Tr1} ($Bottom_{Tr1}$)
Calculation of Soil Composition

Figure 6-11: Algorithm Module for 2C6 with Different directions

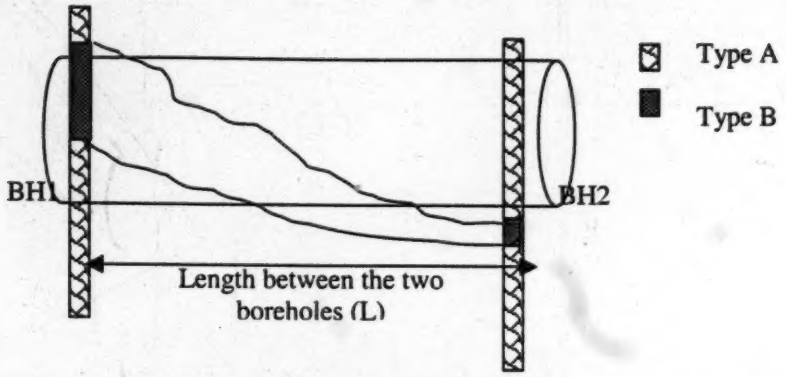


Figure 6-12: Transition of two soils with an intermediate continuous layer both at top and bottom

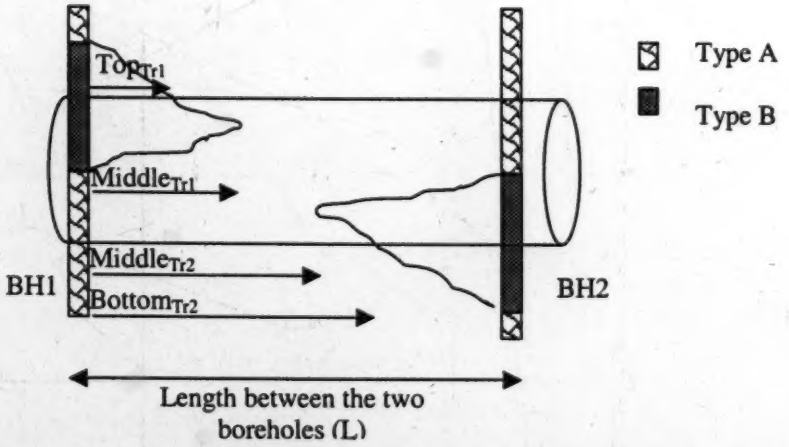


Figure 6-13: Transition of two soils with an intermediate pocket with transition at both at top and bottom

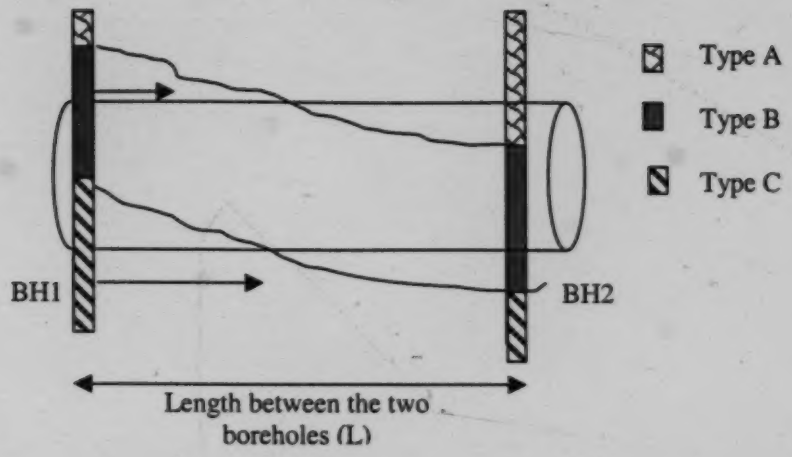


Figure 6-14: Transition of three soils with transition at both at top and bottom

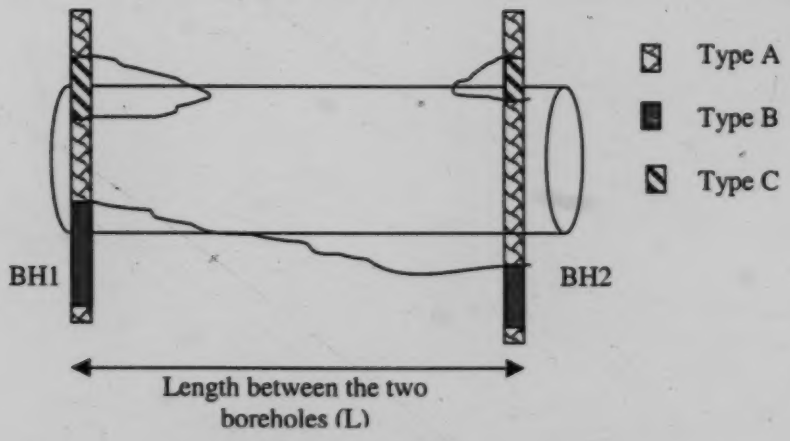


Figure 6-15: Transition of three soils with pockets from one soil

6.4.6 Rules of Transitional Algorithm Modules when Soil Pockets are available

When soil pockets (for example soil B) can be observed in some boreholes, it is possible that the probability of moving from Soil B to Soil B at the successive boreholes may be zero. In that situation, the end result of the probability of moving from Soil B to the

continuous layer Soil A, is 1 leading to an absorbing state for Soil B. This creates a contradiction to the rules outlined in the previous sections. Table 6-7 shows an example of having an absorbing state where the probability of moving from Soil B to Soil B is zero and the probability of moving from Soil B to Soil A is 1 in the top transition matrix.

Table 6-7: Absorption States in Top Transition Matrix

Probabilities

	Soil A	Soil B
Soil A	0.67	0.33
Soil B	1.00	0.00

Transitions

	Soil A	Soil B
Soil A	10	5
Soil B	8	0

The transition equations stated in 6.3 and 6.4 cannot be applied in this situation. According to equation 6.3, if the random number is less than P (B/A), the soil is A or else the soil is B. When the P (B/A)=1, the end result is that it is always Soil A. This concludes that Soil B is only seen in the borehole. Since, it is not possible to accept that hypothesis, the algorithm for predicting the transition points when P (B/A)=1 is modified to consider the soil type at the future location and adjust the probabilities. There are two possibilities of encountering Soil A in the next borehole. It could be from Soil B to Soil A, or Soil A to Soil A. Hence, the modified transition probabilities are calculated as follows, only when the usual P (B/A)=1 and P (B/B)=0.

$$Modified\ P(B/A) = \left[\frac{Number\ of\ observed\ transitions\ from\ B\ to\ A}{Number\ of\ observed\ transitions\ \ ending\ at\ A}\right] \quad ...(6.14)$$

$$Modified\ P(A/A) = \left[\frac{Number\ of\ observed\ transitions\ from\ A\ to\ A}{Number\ of\ observed\ transitions\ \ ending\ at\ A}\right] \quad ..(6.15)$$

6.5 Limitations and Further Improvements for Transitions of Soils between the Boreholes

All the soil transition scenarios stated in Table 6-5 and Table 6-6 show smooth transition curves from one borehole to another. Figure 6-3 and Figure 6-4 demonstrate the transitions that may occur between the boreholes due to changes in the direction of the soil profiles. As there is an uncertainty in predicting the shape of the profile between the boreholes, further analysis is required to determine the exact nature of the soil profile between the boreholes, which is not addressed in this chapter. Figure 6-16 shows the different variations that may be possible between the two boreholes for Scenario # 5 in Table 6-5.

Variations indicated in Figure 6-16 can be detected with elevations of the soils using the preliminary method proposed by Allouche (2001). Allouche and Ruwanpura (2001) predicted the existence of soil families along the tunnel based on an analytical method. The method presented in Allouche (2001) is an extension to that study. He argues that the elevation of a soil at any target point depends on four factors.

a) The elevation of the same soil in the boreholes in the vicinity of the tunnel.

b) The general elevation of the same soil under a particular soil family. For example, if the profile is for soil type 2 and particular borehole has soil family 85251, this is the average elevation of soil type 2 within soil family 85251.

c) The elevation of a soil type within a soil family based on the existence of the soil families on either side of the target point along a tunnel path. For example, the average elevation of soil 2 within borehole that has family 85251 when the previous borehole family is 851 and the next borehole family is 751 ns the tunnel path.

d) Distance from the target point to the boreholes in the vicinity of the tunnel.

The elevation of the soil profile would change based on the three types of elevation stated above, which provides an analytical approach to determine the changes in directions for the soil profiles. With this approach it is probable to identify whether the direction of the soil would differ from the scenarios stated in Tables 6.4 and 6.5. However, a detailed validation is required upon completing the final formula to calculate the elevation of a soil, as suggested by Allouche (2001).

The other approach to detect the profile of the soil between the two boreholes is to apply a mathematical formula to draw or interpolate the probable profile. There are many mathematical formulas for interpolation purposes. One such method is the "Spline Function" discussed by various researchers, including De Boor (1978) for interpolation purposes. The real explosion in the theory, and in practical applications, began in the early 1960s. Spline functions are used in many applications such as interpolation, data fitting, numerical solution of ordinary and partial differential equations (finite element

method), and in curve and surface fitting. Another option would be to incorperate some stochastic sampling within the simulation environment to determine how many transitions may encounter at top and bottom elevations of the tunnel between the two boreholes. Hence, it is recommended that further analysis in this area would provide an opportunity to assess the transition pattern between two boreholes which can be modeled using special purpose simulation.

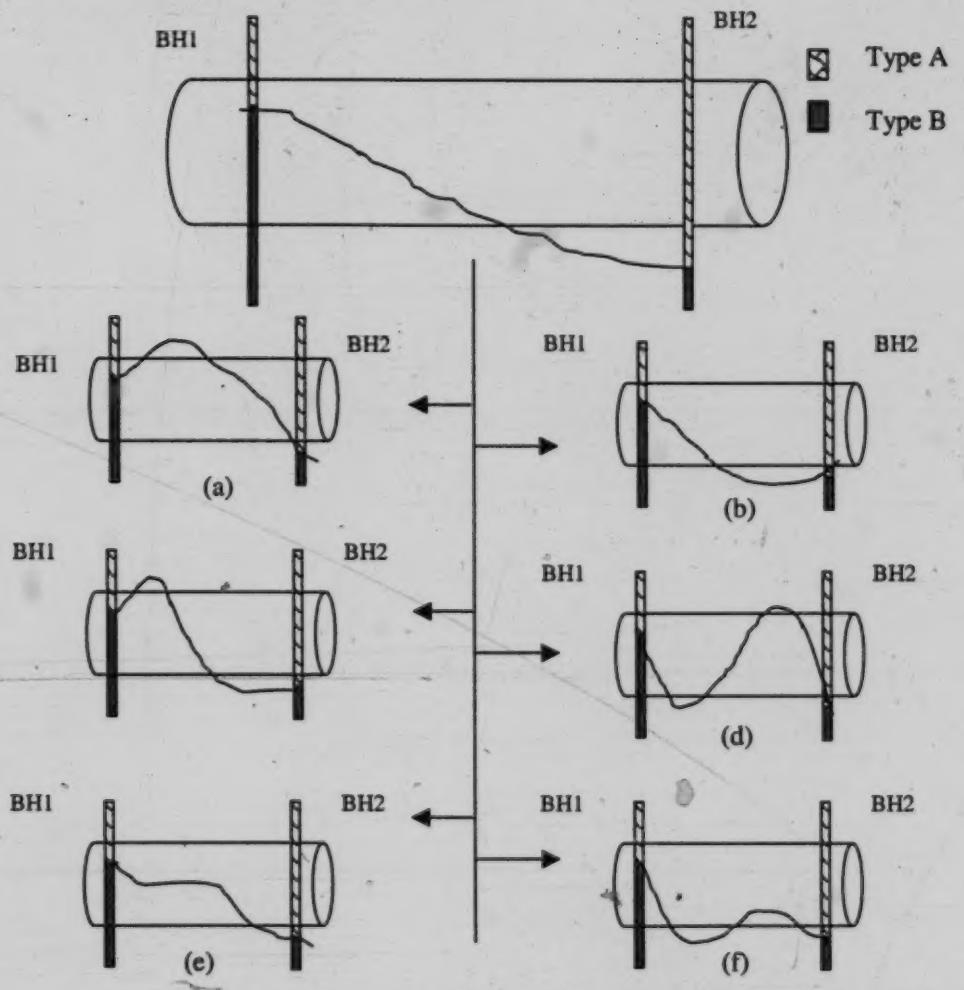


Figure6-16: Various variations for Scenario # 5

6.6 Conclusions

This chapter presented the development of new algorithm modules to predict the soil transition points along a tunnel path using transitional probabilities. This new approach predicts the transition points along the tunnel using an analytical method rather than using approximations or assuming arbitrary transition points. Based on the transition points, the composition of soils and boring rates are calculated to arrive at the productivity of tunnel construction operations. Several combinations of soil transitions for many scenarios have been presented which are implemented within a special purpose simulation template in tunneling and documented in Chapter 7.

The modeling approach can be applied even without the soil prediction method explained in Chapter 5 although the accuracy of the soil profile cannot be justified between the boreholes. If the boreholes cannot provide a conclusive image of the family of the soils, it is not possible to apply the soil prediction methodology presented in Chapter 5. The application of the soil prediction methodology for the NEST tunnel has assisted in determining additional observation points (called artificial boreholes) to more accurately predict the soil transition points. In the absence of soil families, the information in boreholes is the only source of information for arriving at the transition points for simulation purposes; an example of this is validated in Chapter 8.

Chapter 7: Modeling of Soil Transitions within Tunnel Simulation Template

7.1 Introduction

The modeling algorithms documented in Chapter 6 are implemented within the tunnel simulation template described in Chapter 3. The Simphony simulation engine provides an easy and flexible modeling environment to implement the soil transition concepts. The one-way tunnel template has been modified with additional modeling elements and algorithms without losing the originality of the tunnel simulation template. It is also possible to adopt the original configuration of declaring soil segments without using new modeling elements. In the original tunneling template, there is a soil segment element, which allows the user to add the length of the soil section and select the soil type from a list. The soil segment element was further modified to input the composition of the soil, as shown in Figure 3.13.

Section 7.2 presents the new modeling elements added to the tunnel template and any enhancements made to the original modeling elements without losing their original functionality. Section 7.3 shows a modeling layout of the new modeling elements. Section 7.4 provides a sample application to depict the scenario # 1 explained in Chapter 6. Section 7.5 presents the simulation analysis for Figure 6.4 stated in Chapter 6.

7.2 New Modeling Elements

The following five additional modeling elements were added to model the soil transition points for tunnel construction operations. They are explained below.

a) Markov Soil Assign

b) Soil State

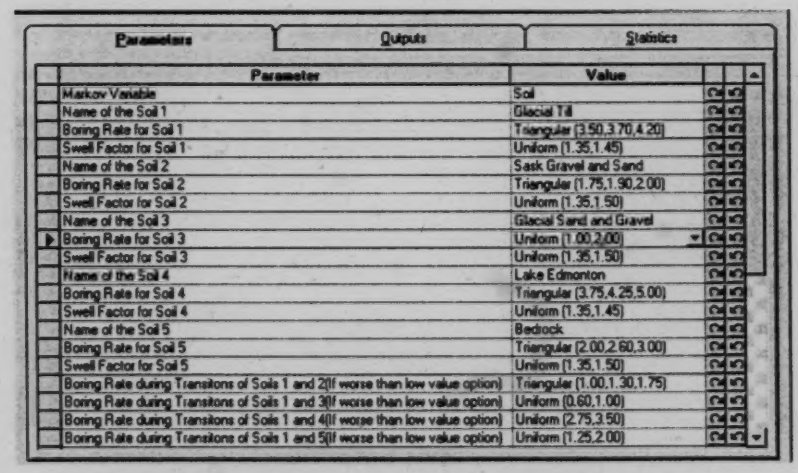
c) Soil Section for two continuous soils

d) Soil Section for three continuous soils

e) Soil Section for one continuous soil and one soil pocket.

f) Soil Section for two continuous soils and one soil pocket.

g) Borehole



Parameter	Value
Markov Variable	Soil
Name of the Soil 1	Glacial Till
Boring Rate for Soil 1	Triangular (3.50,3.70,4.20)
Swell Factor for Soil 1	Uniform (1.35,1.45)
Name of the Soil 2	Sask Gravel and Sand
Boring Rate for Soil 2	Triangular (1.75,1.90,2.00)
Swell Factor for Soil 2	Uniform (1.35,1.50)
Name of the Soil 3	Glacial Sand and Gravel
Boring Rate for Soil 3	Uniform (1.00,2.00)
Swell Factor for Soil 3	Uniform (1.35,1.50)
Name of the Soil 4	Lake Edmonton
Boring Rate for Soil 4	Triangular (3.75,4.25,5.00)
Swell Factor for Soil 4	Uniform (1.35,1.45)
Name of the Soil 5	Bedrock
Boring Rate for Soil 5	Triangular (2.00,2.60,3.00)
Swell Factor for Soil 5	Uniform (1.35,1.50)
Boring Rate during Transitons of Soils 1 and 2(If worse than low value option)	Triangular (1.00,1.30,1.75)
Boring Rate during Transitons of Soils 1 and 3(If worse than low value option)	Uniform (0.60,1.00)
Boring Rate during Transitons of Soils 1 and 4(If worse than low value option)	Uniform (2.75,3.50)
Boring Rate during Transitons of Soils 1 and 5(If worse than low value option)	Uniform (1.25,2.00)

Figure 7-1: Markov Soil Assign Modeling Element

The purpose of the *Markov Soil Assign* modeling element is to define the various soil types that may be encountered during tunneling. Properties of each soil type, such as boring rate, and swell factor (Figure 7-1), can be declared within this element for up to five soil types, and it will provide this information to the other modeling elements when

requested. If the boring rate when two soils interact is worse than the lowest boring rate of the two soils, the new boring rate must be entered as input.

The Soil State modeling element is a child element within the Markov Soil Assign element. The soil state element is designed to depict the matrix inputs. The present soil state, future soil state, and the transitional probability (top, center and bottom) values between the two soil states and the method of calculating the boring rate (explained in Section 6.4.3) are inputs for the soil state modeling element. Figure 7-2 shows a sample of the soil state. A two state transitional probability matrix is formed using four soil state modeling elements (depicted later in this chapter), and the present state, future state, and transitional probability values are shown on the face of the modeling element for any user to observe if a mistake has been made in inputting values.

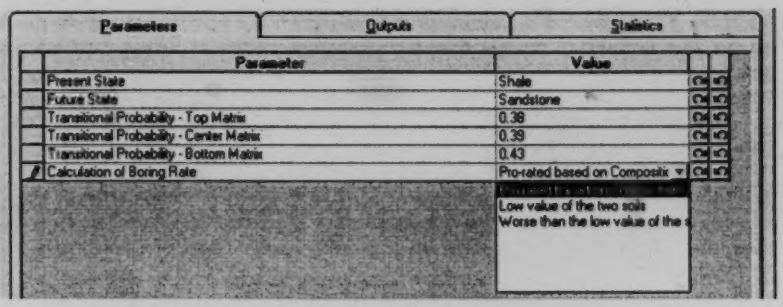


Figure 7-2: Soil State Modeling Element

Four new soil segment elements (two continuous soils, three continuous soils, one continuous soils with a soil pocket, two continuous soils with a soil pocket) replace the soil segment of the original tunnel template, although the inputs remain same except the type of soil is no longer being picked from an arbitrary list as in the original template. Figure 7-3 shows the four different soil modeling elements. The various scenarios explained in Chapter 6 are modeled within each element based on the number of soils

involved in the transition. For example, various combinations of one continuous soil and one soil pocket (shown in Table 6.5) were divided into several modules, based on the soil types at the top and bottom of the start and end of the soil section (between the boreholes). Table 7-1 depicts the categorization of the modules.

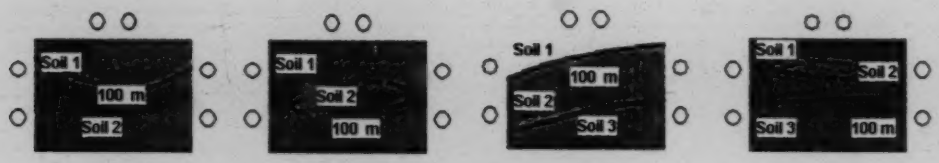


Figure 7-3: Soil Modeling Elements

Borehole is the other additional modeling element (Figure 7-4), which holds the details of the borehole information for a particular location along the tunnel alignment. The soil types and their end elevations in the borehole logs are the inputs. Further, the status of the soil can be defined as continuous or pocket. If the gradient of the tunnel is not the same from the tunnel start and the end, the top elevation of the tunnel that crosses the borehole is also an input.

Parameters | Outputs | Statistics

Parameter	Value
Borehole No	178
Top Elevation of the Tunnel crossing the borehole	675.71
Soil Type 1	Shale
End Elevation (m) of Soil Type 1	674.48
Status of Soil	Continuous
Soil Type 2	Sandstone
End Elevation (m) of Soil Type 2	671.73
Status of Soil	Continuous
Soil Type 3	Shale
End Elevation (m) of Soil Type 3	670.21
Status of Soil	Continuous
Soil Type 4	
End Elevation (m) of Soil Type 4	0.00
Status of Soil	Continuous
Soil Type 5	
End Elevation (m) of Soil Type 5	0.00
Status of Soil	Continuous

Figure 7-4: Borehole modeling element

Table 7-1: Categorization of the Scenarios based on soil types at top and bottom of the soil section

Scenario	Top Layer at Start	Top Layer at End	Bottom Layer at Start	Bottom Layer at End	Remarks
101	A	A	A	A	
102	A	A	A	A	BH2 No Second Layer
103	A	A	A	A	BH1 No Second Layer
107	A	A	A	B	BH1 No Second Layer
115	A	A	A	B	
106	A	A	B	A	BH2 No Second Layer
113	A	A	B	A	
109	A	A	B	B	
105	A	B	A	A	BH1 No Second Layer
114	A	B	A	A	
121	A	B	A	B	
123	A	B	A	B	BH1 No Second Layer
110	A	B	B	A	
120	A	B	B	B	
104	B	A	A	A	BH2 No Second Layer
112	B	A	A	A	
111	B	A	A	B	
108	B	B	A	A	
118	B	A	B	B	
124	B	A	B	A	BH2 No Second Layer
116	B	A	B	A	
119	B	B	A	B	
117	B	B	B	A	
122	B	B	B	B	

BH1= Borehole 1, BH2=Borehole2

Additional input parameters were added to the Tunnel Parent modeling element: the top elevation of the tunnel at its start and the grade of the tunnel. The start and end elevation of each of the soil modeling elements refer to the grade input parameter and adjust the top and bottom elevation at start and end of each of the soil sections.

7.3 Layout of the New Modeling Elements

Figure 7-5 depicts the modeling layout of the new modeling elements. The original layout of the tunnel template and the modified tunnel template are very similar in terms of the modeling connections. The first soil segment is connected to the Breakout Track element and the last soil segment is connected to the TBM element. The borehole elements are connected to the left and right connection points of the soil segments. The Markov Soil Assign element is not connected to any of the modeling elements and remains in the same level as the soil segment elements. A sub-element level of the Markov Soil Assign element comprising the matrix of the soil states is shown in Figure 7-6. The first soil state of each row is connected with an *"entity generation"* modeling element from the Simphony general-purpose simulation template. The last soil state of each row is also connected to the *"terminate"* element of the general-purpose simulation template. The modeling algorithm of the new tunnel simulation template is shown in Figure 7-7

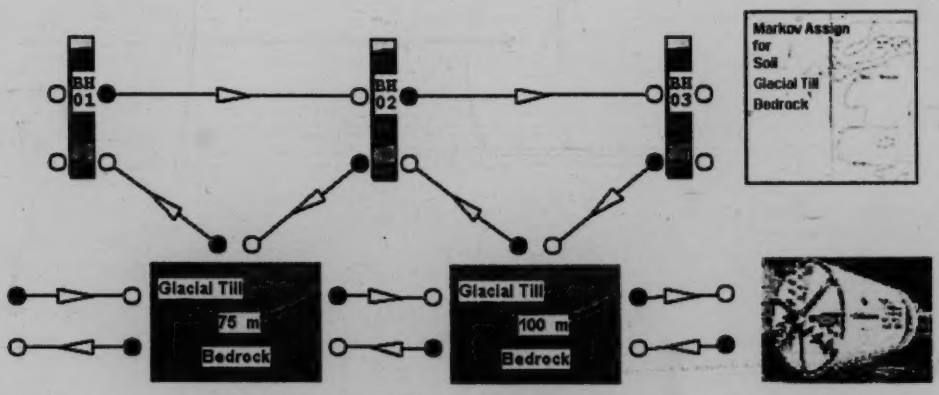


Figure 7-5: New Modeling Layout

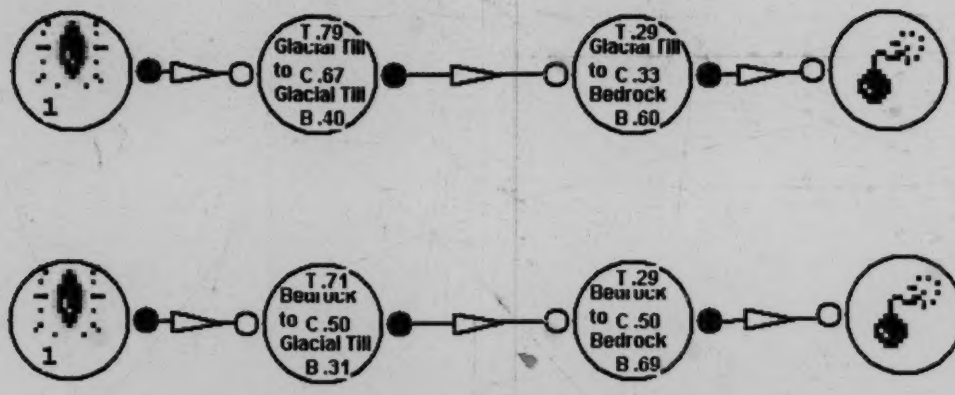


Figure 7-6: Modeling Layout of the Probability Transition Matrix

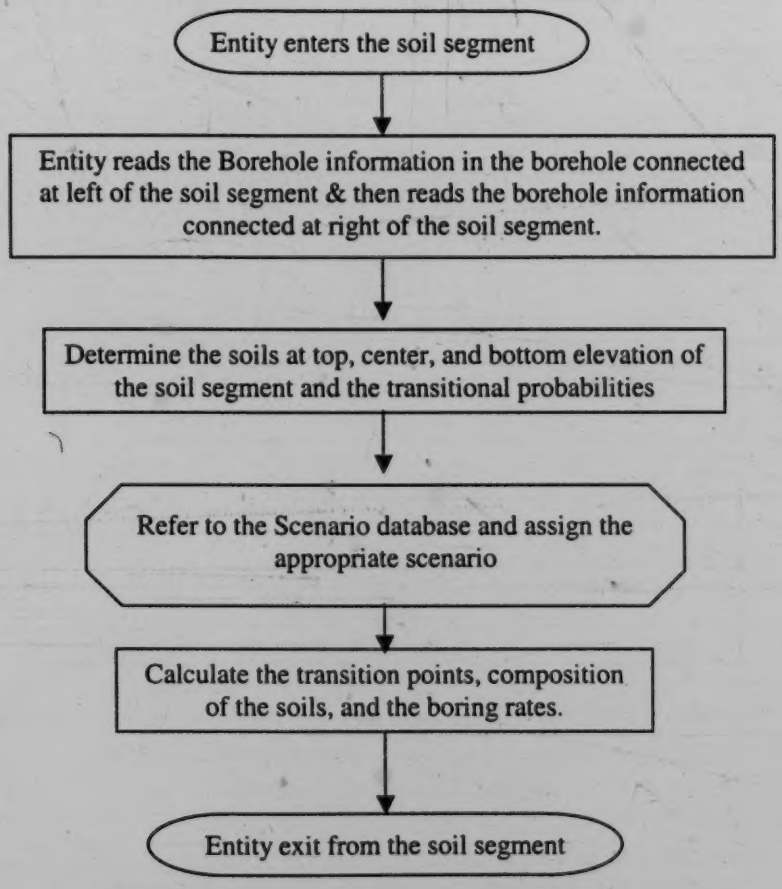

Entity enters the soil segment
Entity reads the Borehole information in the borehole connected at left of the soil segment & then reads the borehole information connected at right of the soil segment.
Determine the soils at top, center, and bottom elevation of the soil segment and the transitional probabilities
Refer to the Scenario database and assign the appropriate scenario
Calculate the transition points, composition of the soils, and the boring rates.
Entity exit from the soil segment

Figure 7-7: Modeling algorithm for Markov Elements

7.4 Example # 1: Transitions of Soils both at top and bottom (Scenario #1)

It is a two-soil situation with soils "Glacial Till" (type 5) and "Bedrock" (type 1). During the first 75 meters (first soil segment), the transition occurs both at top and bottom from bedrock to glacial till whereas during the next 100 meters (second soil segment), the transition occurs both at top and bottom from glacial till to bedrock. The simulation results based on ten (10) runs are shown in the following figures. Figure 7-8 shows the overall tunnel advance rate of the entire 175 meters using the first calculation method (pro-rated tunnel boring rates) explained in Chapter 6. The top transition in the first soil segment occurs between 18 and 26 meters, and the bottom transition occurs between 52 and 64 meters. The top transition of the second soil segment occurs 77 and 86 meters whereas the bottom transition occurs between 9 and 13 meters. The boring rates for the section 1 using the pro-rated boring rates for one of the simulation runs is in Figure 7-9.

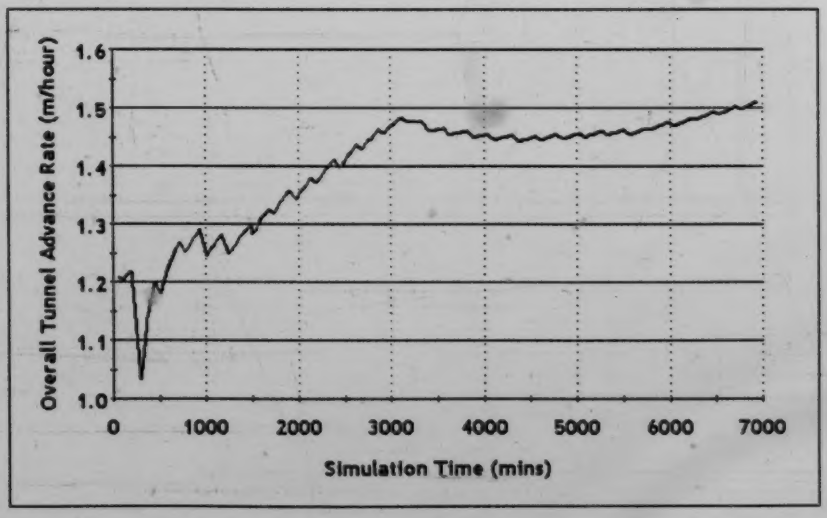


Figure 7-8: Overall tunnel advance rate using pro-rated calculation method

However, it was not possible due to co-existence of various soils and soil families in the area, which is evident in Figure 5.5. The general observations made in Section 5.2.1 explain some of the regularities and irregularities among the soils in the area. The availability of other borehole data, such as City of Edmonton boreholes, could divide the area into smaller areas with similar properties in terms of surficial soil or soil families. Most of the City boreholes do not have a complete profile from the surface to the bottommost layer, and are therefore difficult to adopt with the ARC data to make accurate predictions. The availability of more borehole data with complete profiles could provide a better image of the study area by dividing them into better clusters.

Although the general probabilities of existence of soils or soil families stated in this chapter consider the entire study area to derive the general probability values, final probability values (such as PCE) to derive the probability of existence of a soil or a soil family are concentrated on a specific area of the tunneling. The general probabilies for probability analysis are either increased or descreaed based on the availability of soils and soil families in the area to derive the final analysis. For example, although the PCE probability values in Table 5-9 show more generic values of PCE (Equation 5.5) considering the entire study area, the weightage factors calculated using Equation 5.6 adjust these general proabilities specific to the tunnel location considering the availaibilty of specific soil families in the area. The avilability of more data either from the City of Edmonton or other sources will provide a more accurate and enhanced image of the study area to increase or decrese the general and specific probability values discussed in the chapter.

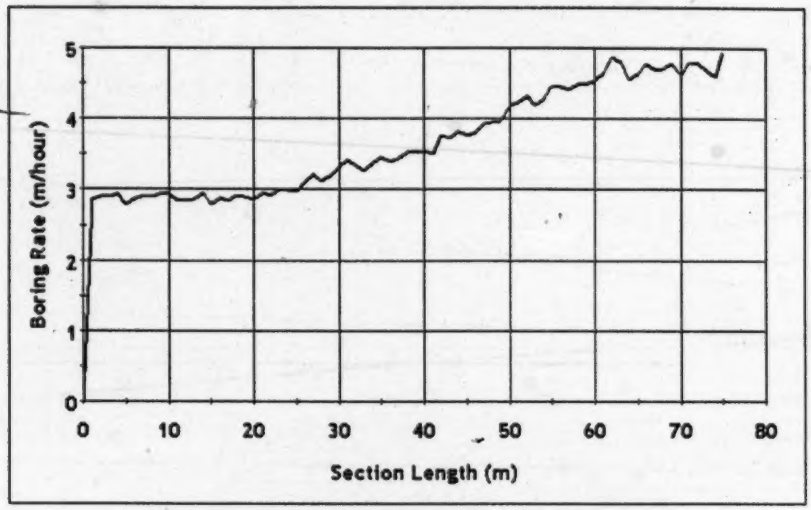


Figure 7-9: Boring rates across the first soil segment

The second test assumes that that the boring rate during transition is worse than the least boring rate soils (calculation method 3). Figures 7-10 and 7-11 show the transitions statistics of both soil section 1 and 2 using the soil calculation method 3. Figures 7-12, 7-13 and 7-14 show boring rates for soil section 1, section 2, and the overall tunnel advance rates of the simulation runs.

Parameters | Outputs | Statistics

Statistic	Runs	Mean	First StdDev	Global StdDev	Minimum	Maximum	Graphs
1st Top Transition Point	10	23.60	0.00	3.10	18.00	29.00	View
1st Bottom Transition Point	10	60.20	0.00	3.08	57.00	65.00	View
2nd Top Transition Point	10	0.00	0.00	0.00	0.00	0.00	View
2nd Bottom Transition Point	10	0.00	0.00	0.00	0.00	0.00	View
Left Transition Point of Pock	10	0.00	0.00	0.00	0.00	0.00	View
Right Transition Point of Poc	10	0.00	0.00	0.00	0.00	0.00	View
Boring Rate (m/hr)	10	2.91	1.01	0.12	1.59	4.97	View
Swell Factor	10	1.44	0.05	0.01	1.35	1.50	View

Figure 7-10: Transition statistics of Soil Section 1 – Calculation Method 3

Parameters | Outputs | Statistics

Statistic	Runs	Mean	First StdDev	Global StdDev	Minimum	Maximum	Graphs
1st Top Transition Point	10	82.80	0.00	3.65	78.00	91.00	View
1st Bottom Transition Point	10	11.20	0.00	1.23	10.00	13.00	View
2nd Top Transition Point	10	0.00	0.00	0.00	0.00	0.00	View
2nd Bottom Transition Point	10	0.00	0.00	0.00	0.00	0.00	View
Left Transition Point of Pock	10	0.00	0.00	0.00	0.00	0.00	View
Right Transition Point of Poc	10	0.00	0.00	0.00	0.00	0.00	View
Boring Rate (m/hr)	10	2.58	0.82	0.05	1.57	4.98	View
Swell Factor	10	1.42	0.03	0.01	1.36	1.50	View

Figure 7-11: Transition statistics of Soil Section 2 – Calculation Method 3

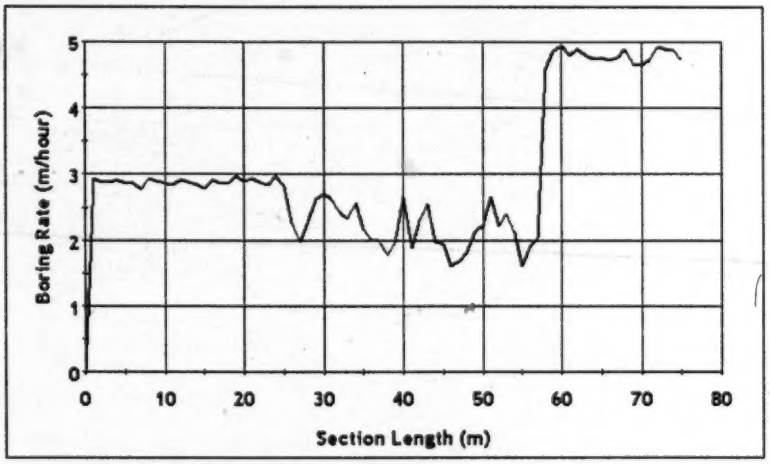


Figure 7-12: Boring rates across Soil Section 1 – Calculation Method 3

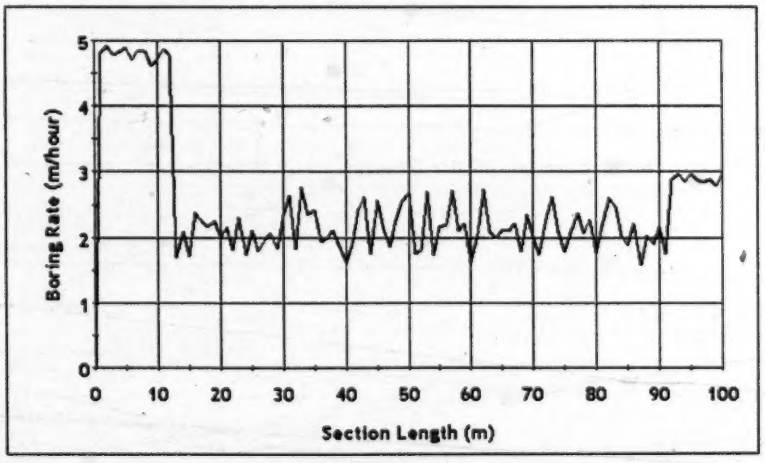


Figure 7-13: Boring rates across Soil Section 2 – Calculation Method 3

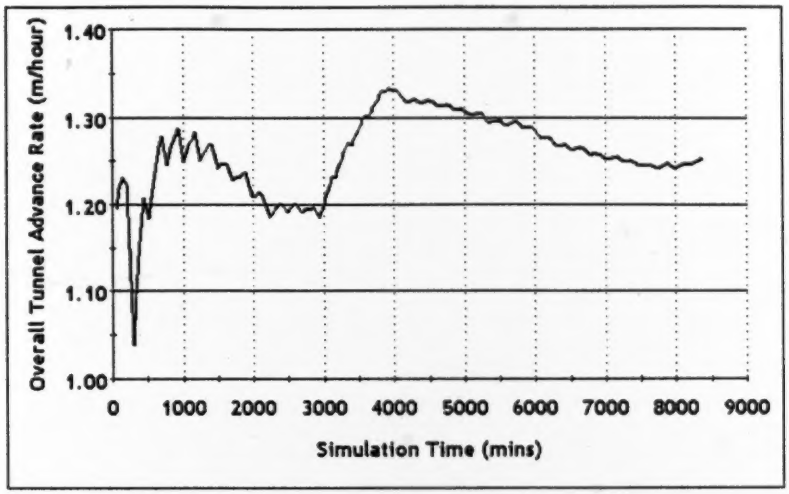


Figure 7-14: Overall Tunnel Advance Rate using Calculation Method 3

7.5 Example # 2: Simulation Results based on the Model in Figure 6-4

This section presents the simulation results using seven soil sections, as shown in Figure 6-4. The total length of the tunnel is 485 meters. The calculation of boring rates was set to method 3 when both soils interact with each other. The model layout of this example is shown in Figure 7-15.

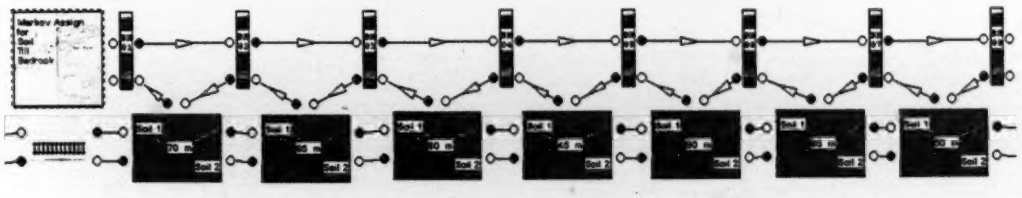


Figure 7-15: Layout of the Boreholes and Soil Sections depicting Figure 6-4

The results based on 20 simulation runs are shown in Table 7-2. The table shows the minimum, maximum, average, and standard deviation of the top and bottom transitions of each soil section.

Table 7-2: Results of the 20 Simulation Runs

Section	Length (m)	Top Transition Point				Bottom Transition Point			
		Min	Max	Avg.	SD	Min	Max	Avg.	SD
1	70	16	27	21.5	3.17	51	60	55.35	2.58
2	65					17	34	27.85	4.04
3	80								
4	45	31	43	37.1	2.81				
5	90								
6	85	20	32	26.3	4.03	63	77	69.05	3.95
7	50								

The overall tunnel advance rate is shown in Figure 7-16 from Simulation Run # 1. Figure 7-17 depicts the output results and the representation of the boring rate for Soil Section 6.

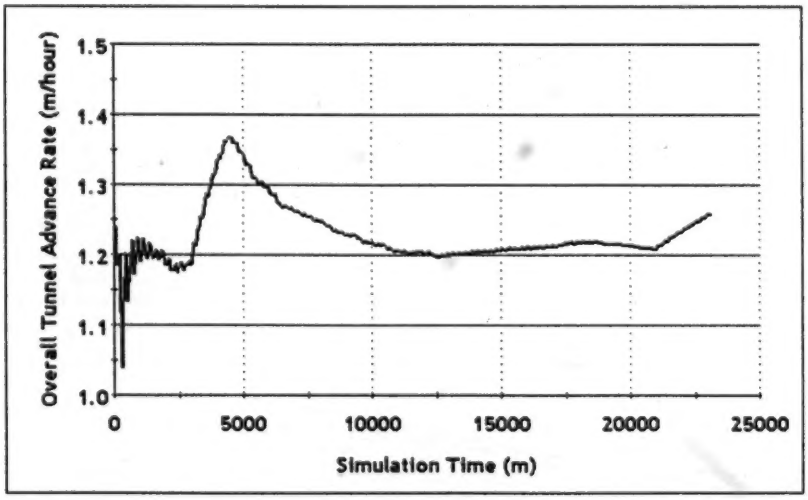


Figure 7-16: Overall Tunnel Advance Rate using Calculation Method 3

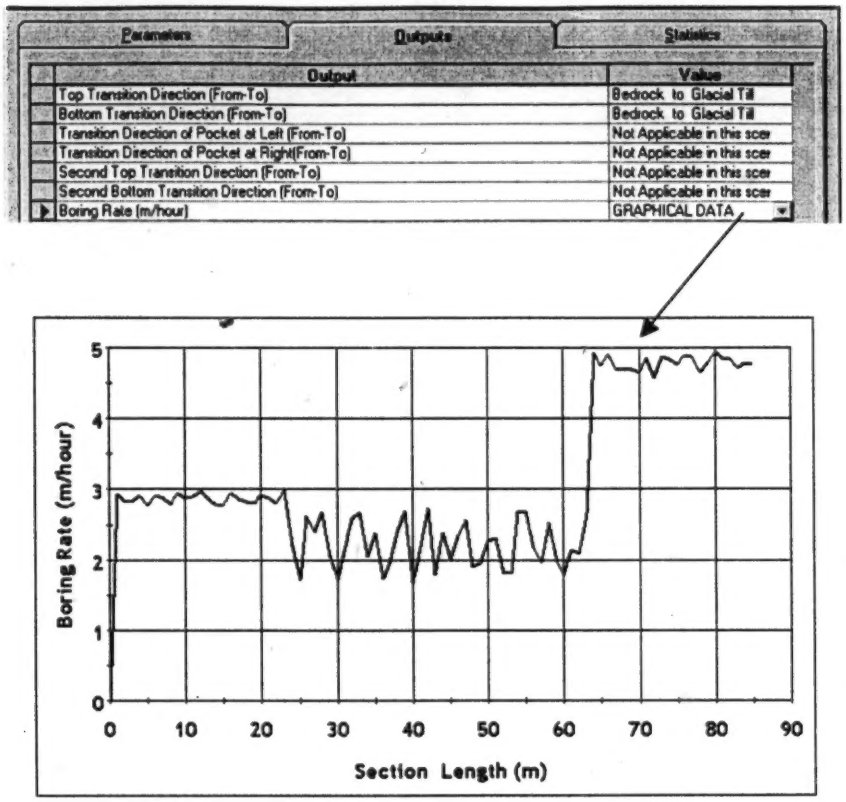


Figure 7-17: Results for Soil Section 6 with Boring Rate

Figure 7-17 shows how the tunnel advance rate moves up and down based on the composition of the soils. Figure 7-18 depicts the profile of the Glacial Till (end elevation) and Bedrock (start elevation) based on the simulation results. The minimum, average, and maximum transitions points are plotted with the tunnel length and the elevations of the soil.

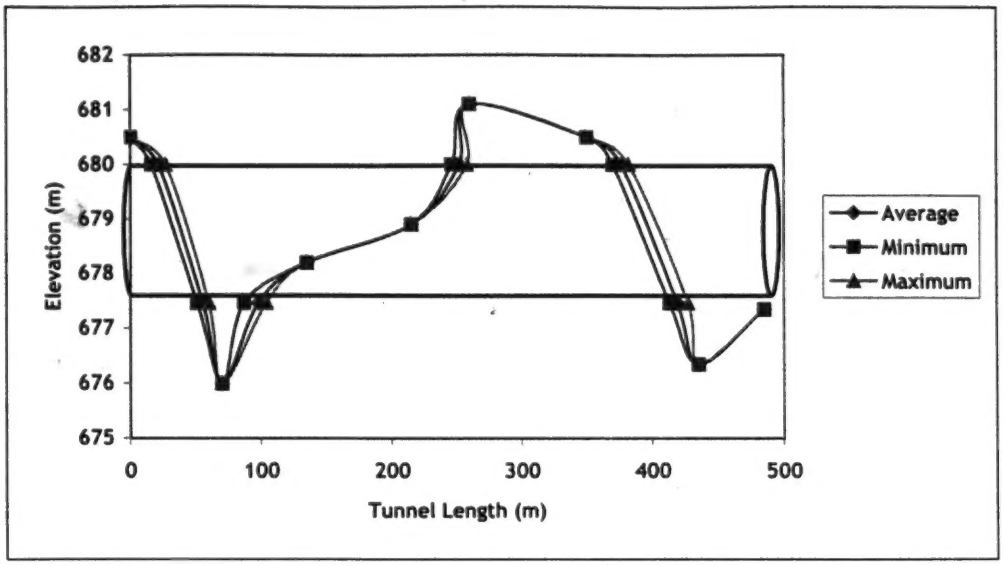


Figure 7-18: Profile of the soils based on simulation results

7.6 Conclusions

This chapter presented the design and implementation of the soil transition algorithms outlined in Chapter 6. The modeling elements were designed not to lose the originality of the tunnel template discussed in Chapter 3. The modified tunnel template allows the user to predict the transition points along the tunnel if two or more soils interact with each other. The elevations of the tunnel at seven depth levels provide the sample representation of the soil profile using transitional probabilities. The transitional probabilities are then used to predict the transition points.

Chapter 8: Application and Validation of the Modeling Algorithms to Predict Soil Transitions

8.1 Introduction

The development of predicting the transitions of soils for special purpose simulation for tunnel construction operations leads to improvement in the following areas:

1. Prediction of the soil transition points along the tunnel is based on the deterministic borehole data, the probability analysis explained in Chapter 5, and the soil transition algorithms discussed in Chapter 6 using transitional probabilities. This provides a structured approach rather than arbitrarily deciding (or approximating) the soil transitions (or the compositions of the soils).
2. Calculation of the soil compositions and determining the productivity factors based on the predicted soil transitions rather than arbitrarily assuming (approximating) the composition of the soils by observing the borehole data.

This chapter presents the analysis based on a case study to prove the above mentioned improvement areas. The case study shows an actual tunnel, which was completed in 1994/5. Soil prediction algorithms explained in Chapter 6 are applied in this case study without using the soil characterization method explained in Chapter 5, to show that the deterministic data in the borehole could only be used to obtain the results through simulation in the absence of soil characterization. The actual productivity data for this tunnel was obtained using the daily report logs and consultation with the site supervisor and the site engineer. This particular tunnel was excavated in Bedrock comprised of shale

and sandstone. The soil characterization method explained in Chapter 5 could only be applied to the major soil categories such as Bedrock, Clay Till, etc. Since the tunnel boreholes have detailed soil descriptions, and only within the specific bedrock types in the vicinity, the transitions of shale and sandstone are modeled in this case study which in Section 8.2. The summary of conclusions is then presented in Section 8.3.

8.2 Case Study: Millwoods Tunnel Project

Mill Woods Drainage Improvement - Phase III - Central tunnel project was constructed in 1994 and 1995 by the City of Edmonton. The tunnel was made up of two separate construction methods. The first portion of the tunnel was 2.9 meter finished diameter tunnel excavated using a M-126 Lovat TBM lined with pre-cast concrete segments. The second portion of the tunnel was 3.48 meter finished diameter lined with shortcrete. The first portion has been selected for the analysis as the tunnel simulation template described in Chapter 3 has been designed to simulate tunnels lined with pre-cast liner segments. The tunnel is about 20-25 meters below the ground surface and has a gradient of 0.077% from the main shaft to the removal shaft. There is about 203 meters of curve in the tunnel starting from 687th meter of the tunnel. Table 8-1 shows the top and bottom elevations of the tunnel at each borehole.

Although there were a total of 24 boreholes in the tunnel, only 17 boreholes were in the first portion. 2 boreholes out of those 17 were very shallow and did not represent the soil types in the tunnel elevation. The tunnel is 1651 meters long and the elevation varies from 675.79 meters at the top of the tunnel start to 671.31 meters at the bottom of end (see Table 8-1). Table 8-2 presents the borehole data including the borehole number

in the database and soil types and their elevations within the tunnel elevation. Figure 8-1 shows the conceptual soil profiles between the boreholes from the main shaft to the removal shaft. The Figure 8-1 also shows the length between the boreholes and the most likely soil combination scenarios based on Table 6-3.

Table 8-1: Tunnel Elevations at top and bottom of the boreholes

BH No	Top Elevation of the Tunnel (m)	Bottom Elevation of the Tunnel (m)
177	675.79	672.59
178	675.71	672.51
179	675.61	672.41
180	675.56	672.36
181	675.51	672.31
182	675.42	672.22
183	675.29	672.09
184	675.23	672.03
185	675.16	671.96
186	675.11	671.91
187	675.06	671.86
188	675.01	671.81
189	674.91	671.71
190	674.86	671.66
191	674.76	671.56
194	674.51	671.31

The analysis for this case study was conducted using six models, which are explained below. The input of the soil composition for boring is different in each of the models.

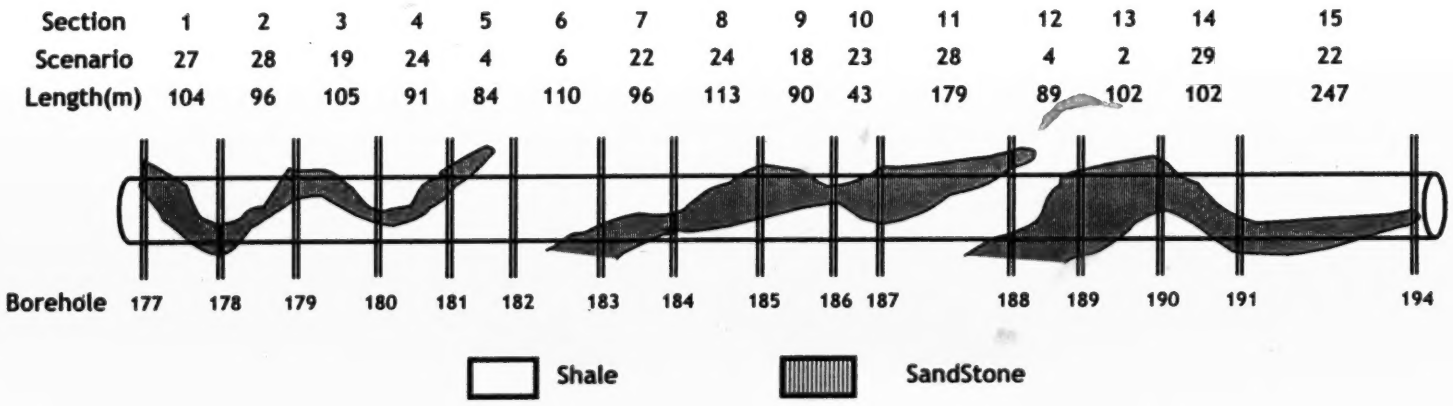


Figure 8-1: Profiles of the Tunnel and its scenarios

Table 8-2: Borehole Data for Mill Woods tunnel project

BH No	SoilType	Start Elevation (m)	End Elevation (m)
177	Shale	681.73	676.70
	Sandstone	676.70	674.87
	Shale	674.87	669.99
178	Shale	676.46	674.48
	Sandstone	674.48	671.73
	Shale	671.73	670.21
179	Shale	677.73	676.05
	Sandstone	676.05	674.99
	Shale	674.99	669.65
180	Shale	686.73	673.79
	Sandstone	673.79	672.39
	Shale	672.39	671.80
181	Shale	677.61	676.09
	Sandstone	676.09	675.17
	Shale	675.17	671.97
182	Shale	676.49	669.17
183	Shale	677.94	674.43
	Sandstone	674.43	671.38
	Shale	671.38	669.55
184	Shale	676.53	674.85
	Sandstone	674.85	672.11
	Shale	672.11	668.60
185	Shale	680.68	676.11
	Sandstone	676.11	673.06
	Shale	673.06	668.03
186	Shale	680.56	674.46
	Sandstone	674.46	673.86
	Shale	673.86	671.21
187	Shale	678.94	675.89
	Sandstone	675.89	672.84
	Shale	672.84	671.01
188	Sandstone	678.22	676.85
	Shale	676.85	673.19
	Sandstone	673.19	668.77
189	Shale	684.20	677.00
	Sandstone	677.00	670.38
190	Shale	678.65	677.28
	Sandstone	677.28	674.07
	Shale	674.07	668.44
191	Shale	676.05	672.09
	Sandstone	672.09	670.87
	Shale	670.87	669.65
194	Shale	676.35	672.85
	Sandstone	672.85	672.24
	Shale	672.24	668.89

- Model 1: The original soil segment modeling element explained in Chapter 3 was used for the entire 1651 meters assuming that the tunnel is excavated in Bedrock. This assumption was applied very arbitrarily as this was the assumption that would have been the best input when the tunnel template was initially developed and applied for various project planning studies.
- Model 2: Modified the assumption in Model 1 by observing at the borehole data and calculate an approximate composition of shale and sandstone. The modified soil section explained in Chapter 3 and depicted in Figure 3.13 was used for this test. This modified soil segment can be inputted with composition percentages of the soils. The composition of shale is 42% and the sandstone is 58% for the overall tunnel. Table 8-3 provides the approximate compositions between each borehole assuming linear interpolations of the soil thicknesses in the boreholes.
- Model 3: Modified the assumption in Model 2 by using 15 separate soil segment modeling elements and applying the compositions between the boreholes. This is the best approximation that is available before developing the soil transitions points and calculating the composition of soils explained in Chapter 6.
- Model 4: Used 15 separate new soil segment elements (explained in Chapter 7) with pro-rated calculation method for boring rate. It is considered for this model that the boring rate within a soil segment depends on the composition of the soils between the two boreholes.
- Model 5: Same method as Model 4 with calculation method 2, and the boring rate is the lesser boring rate of the two soils when the soil types interact with each other inside a soil segment.

- Model 6: Same method as Model 4 with calculation method 3, and the boring rate is worse than the lesser boring rate of the two soils when the soil types interact with each other inside a soil segment. In this case when both shale and sandstone are encountered, it is assumed based on the experience of the tunnel personnel at the City of Edmonton, that sandstone is more difficult to bore than shale (clayshale in this project). When only one soil is prevalent (for example, in section 6 of Figure 8-1) in part of a soil section, the boring rate of the soil in that part is not adjusted at all. For example, in section 6 of Figure 8-1, the boring rate before the bottom transition point is the boring rate of shale and the boring rate after the bottom transition point is worse than the boring rate of sandstone. In this model, it is easy to find out whether there is any change in the productivity based on the soil composition without taking into consideration its composition values. The City of Edmonton tunneling experts suggest that this is the most possible scenario when one soil interacts with others.

The following stochastic data, required for tunnel simulation, was applied for all six models. Twenty simulation runs were used for each stage.

a) Boring rate of shale: Triangular (2.50, 2.70, 3.00) meters per hour

b) Boring rate of sandstone: Triangular (1.75, 1.90, 2.00) meters per hour

c) Boring rate of mixture of shale and sandstone: Triangular (1.00, 1.30, 1.75)

d) Boring rate of bedrock: Uniform (1.75, 3.00) meters per hour

e) Liner installation duration: Triangular (15.00,18.00,25.00) minutes

f) Number and capacity of Muck (dirt) cars: 3 cars with a capacity of 4.60 m^3

g) Swell factor of shale, sandstone and bedrock: Uniform (1.25, 1.45)

h) Train Speeds: Uniform (5.00,8.00) kilometers per hour

The expected duration of boring is 20 to 24 minutes for shale and 30 to 34 minutes for sandstone based on the tunnel advance rate. The expected boring rate is 34 to 60 minutes when both shale and sandstone prevail. The transitional probabilities for models 4, 5, and 6 were calculated based on the procedure described in Chapter 6. The transitions at seven elevation levels and the calculated transitions for each elevation level are shown in Table 8-3. Final top, center, and bottom transitions for the Mill Woods tunnel are presented in Table 8-4. Shale and sandstone are denoted with A and B respectively.

Table 8-3: Transitions at seven elevation levels

		Borehole															
		177	178	179	180	181	182	183	184	185	186	187	188	189	190	191	194
Elevation	Top⁺	B	A	A	A	A	A	A	A	B	A	B	A	B	B	A	A
	Top	B	A	B	A	B	A	A	A	B	A	B	A	B	B	A	A
	Top⁻	B	A	A	A	A	A	A	B	B	B	B	A	B	B	A	A
	Center	A	B	A	A	A	A	A	B	B	A	B	A	B	B	A	A
	Bottom⁺	A	B	A	B	A	A	B	B	A	A	A	A	B	B	A	B
	Bottom	A	B	A	A	A	A	B	A	A	A	A	B	B	B	B	A
	Bottom⁻	A	B	A	A	A	A	B	A	A	A	A	B	B	B	B	A

A = Shale B =Sandstone

Top⁺

	Shale	Sandstone
Shale	7	3
Sandstone	4	1

Top

	Shale	Sandstone
Shale	3	5
Sandstone	6	1

Top⁻

	Shale	Sandstone
Shale	6	2
Sandstone	3	4

Center

	Shale	Sandstone
Shale	6	4
Sandstone	4	1

Bottom⁺

	Shale	Sandstone
Shale	5	5
Sandstone	4	1

Bottom

	Shale	Sandstone
Shale	6	4
Sandstone	3	2

Bottom⁻

	Shale	Sandstone
A	6	4
B	4	1

Table 8-4: Final transitional probability matrices

Top Transition Matrix

	Shale	Sandstone
Shale	16	10
Sandstone	13	6

	Shale	Sandstone
Shale	0.62	0.38
Sandstone	0.68	0.32

Center Transition Matrix

	Shale	Sandstone
Shale	17	11
Sandstone	11	6

	Shale	Sandstone
Shale	0.61	0.39
Sandstone	0.65	0.35

Bottom Transition Matrix

	Shale	Sandstone
Shale	17	13
Sandstone	11	4

	Shale	Sandstone
Shale	0.57	0.43
Sandstone	0.73	0.27

8.2.1 Actual Data of the Mill Woods Case Study

The actual data was obtained from the site log reports prepared by the tunneling supervisor and consultation with the tunneling supervisor and the site engineer. There were some days with no work due to problems other than encountering bad soil conditions. Some of these reasons are TBM breakdown, enlarging undercut, mechanical problems with conveyor, etc. Hence, the days with no progress was not considered in calculating the tunnel advance rate and the duration of the project in order to compare the simulation results. Figure 8-2 provides the actual tunnel advance of the tunnel with at least one meter of progress. Figure 8-3 depicts the productivity for 9-hour shifts. The City of Edmonton adopted two work shifts per day in the latter part of the project. The site log

reports only indicated the total productivity per day. The total productivity was then divided into two equal components to determine the productivity per shift.

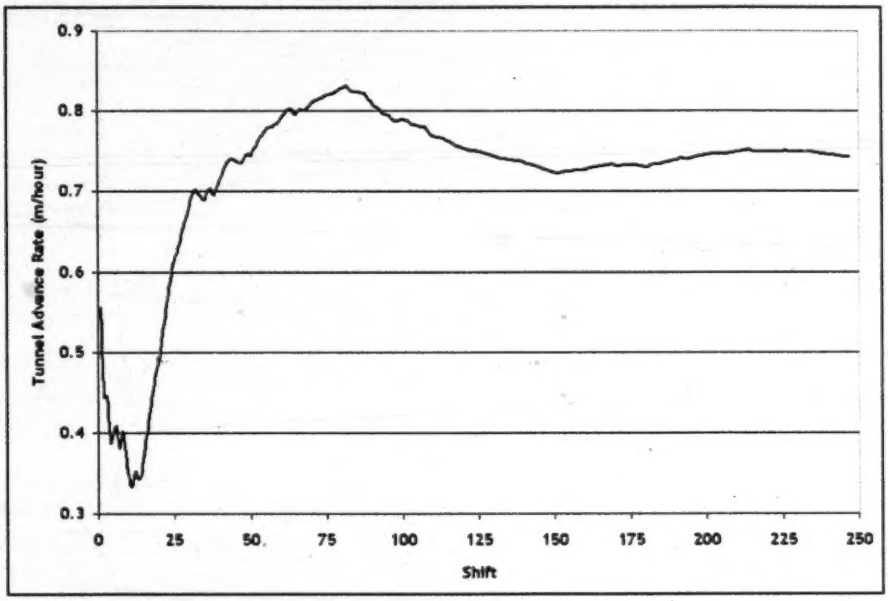


Figure 8-2: Actual Tunnel Advance Rate of the Mill Woods Tunnel Project

The average productivity is 6.68 meters/shift with a minimum of 1 meter per shift and a maximum of 11 meters per shift. Figure 8-2 shows that the tunnel advance rate drops initially and then increases to the highest of 0.83 m/hour. Within that period the progress went up and down several times. The drop of the productivity was mainly due to the curve in the middle of the tunnel. The productivity then fluctuated from the end of the curve to the end of the tunnel at several places along the tunnel.

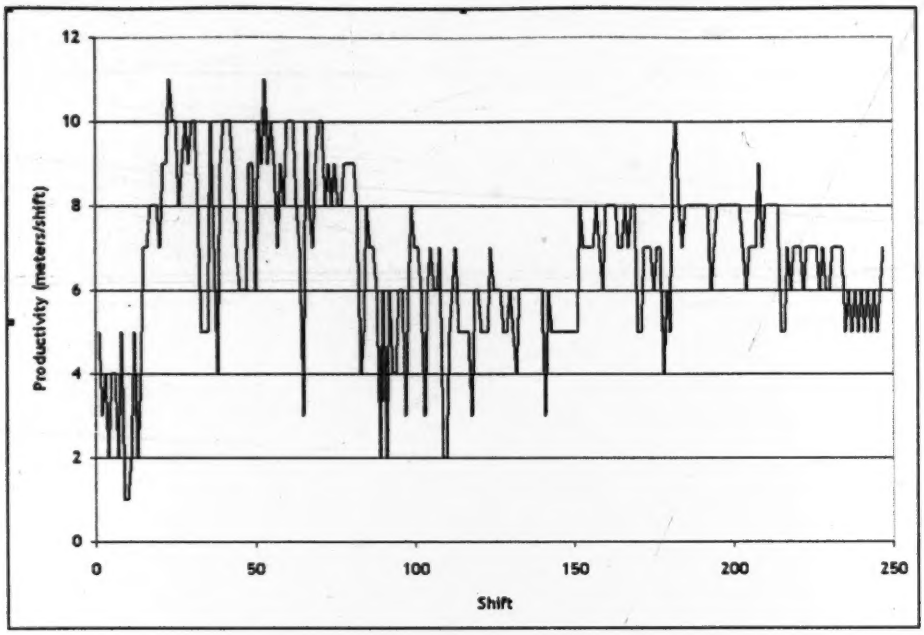


Figure 8-3: Actual Productivity of the Mill Woods Tunnel Project

8.2.2 Results of the Mill Woods Case Study based on Approximate Methods

Tunnel advance rate, productivity per shift, duration and cost of all the models, and the actual productivity data are shown in Table 8-5. Actual cost data has been excluded, as the cost information included in the models is representative of the present basic and operating costs of the City of Edmonton.

Model 1 considers a wide range of boring rates for bedrock, which in turn uniformly calculates the duration of boring between 20 to 35 minutes, as the transition of the soils cannot be determined using this model. The average composition of the soils between the boreholes was calculated to arrive at approximate average composition values for the entire tunnel for model 2 and model 3 using linear interpolation of the soil elevations in the boreholes. Table 8-6 provides the approximate composition percentages

of shale and sandstone for soil section and the overall average approximations. The overall average of shale and sandstone was applied for model 2, and the average values of shale and sandstone were applied to each soil section in model 3.

Table 8-5: Comparison of Productivity, Cost and Schedule Information – Mill Woods

		Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Actual*
Tunnel Advance Rate (meters/hour)	Average	1.02	1.01	1.01	1.01	0.90	0.72	0.74
	Std. Dev.	0.01	0.01	0.01	0.01	0.01	0.01	
Productivity (meters/shift)	Average	9.17	9.05	9.09	9.12	8.06	6.52	6.68
	Std. Dev.	0.14	0.10	0.10	0.13	0.08	0.06	
Cost per meter ($)	Average	1,432.82	1,439.59	1,437.33	1,429.77	1,496.15	1,631.68	
	Std. Dev.	7.57	5.68	3.77	7.38	5.39	6.60	
Duration of the Project - Shifts	Average	180	183	182	181	205	254	247
	Std. Dev.	3	2	2	3	2	3	
		Arbitrary/Approximate			Soil Transition Models			

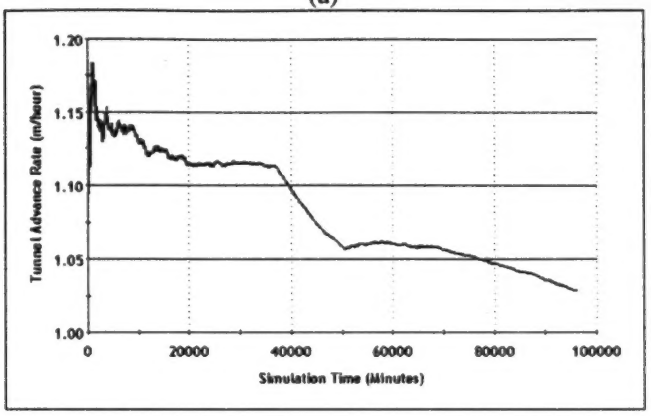
Each of the models 1, 2 and 3 were simulated for 20 runs using approximate percentages of the soils in the boreholes. The results of all three models are very similar to each other. Figure 8.4 presents the tunnel advance rate for models 1 to 3, and the productivity per shift for these models is shown in Figure 8.5. Average productivity per 9-hour shift varies from 9.05 to 9.09 with a standard deviation in the range of 0.10 to 0.14. Productivity per shift varies between 7 to 11 meters per shift. In all three models, the drop in the productivity could be evident when tunneling in the curve. Only model 3 shows a little significance of rise and fall of the productivity throughout the entire tunnel path. None of these models predict the actual productivity. Hence, it could be presumed that the productivity is not affected based on the pure composition of the soil types, as the boring rates for both models 2 and 3 are based on the composition of the soil types. For

example, if the composition is 40% shale and 60% sandstone, the boring rate is 40% of the boring rate of shale plus the 60% of the boring rate of sandstone. Further, the composition of each soil section is assumed to be representative of what can be seen in the borehole logs and therefore deterministic for a soil section.

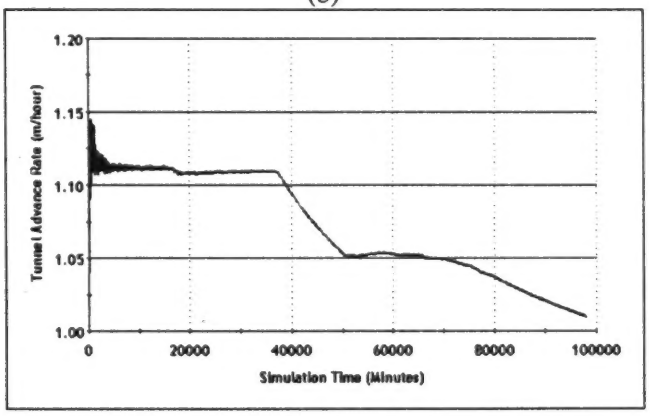
Table 8-6: Approximate composition rates of soil sections

Section	Shale %	Sandstone %
1	45	55
2	41	59
3	32	68
4	27	73
5	5	95
6	37	63
7	81	19
8	64	36
9	30	70
10	44	56
11	56	44
12	72	28
13	62	38
14	21	79
15	18	82
Overall	**42.33**	**57.67**

(a)



(b)



(c)

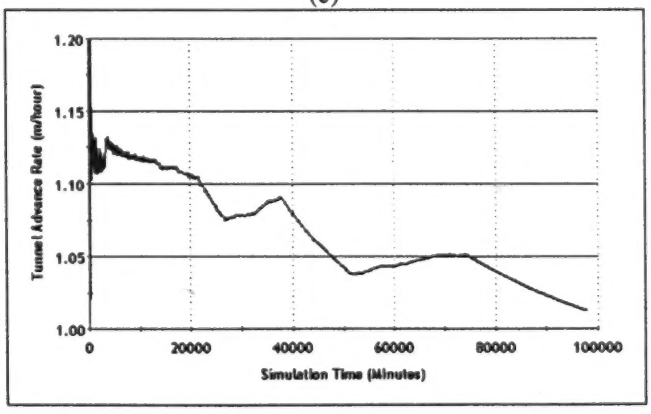
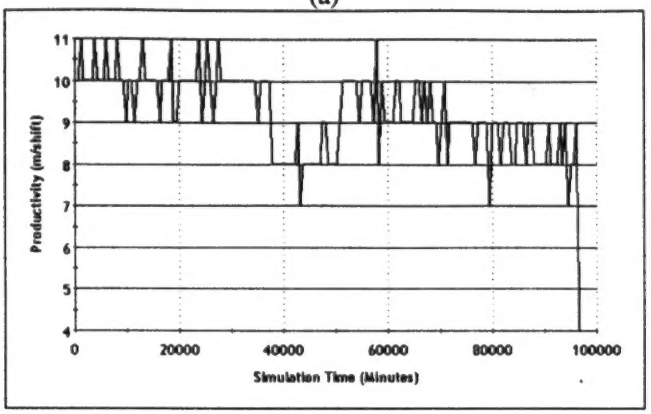
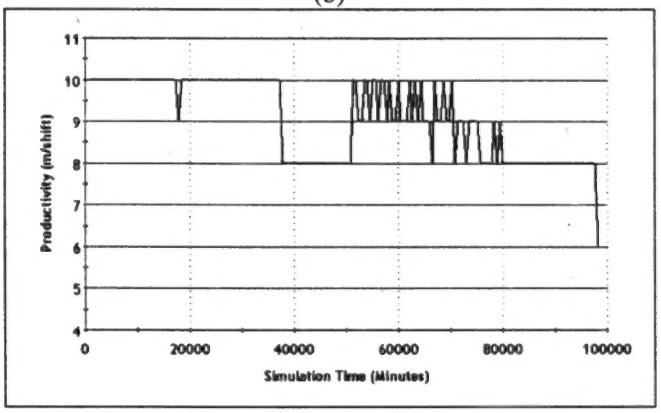


Figure 8-4: Tunnel Advance Rates of the approximate models – (a) Model 1 (b) Model 2 and (c) Model 3 (Mill Woods Tunnel)

(a)



(b)



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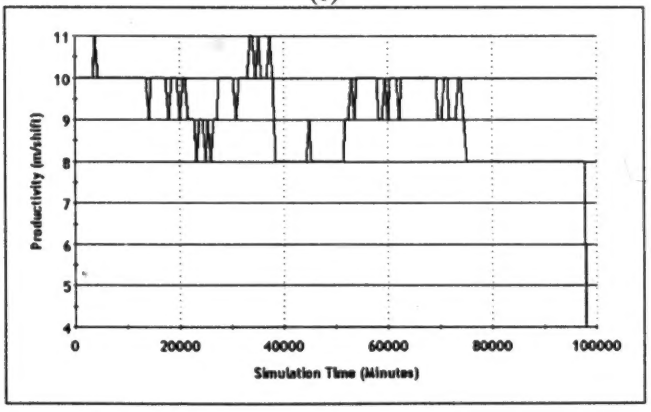


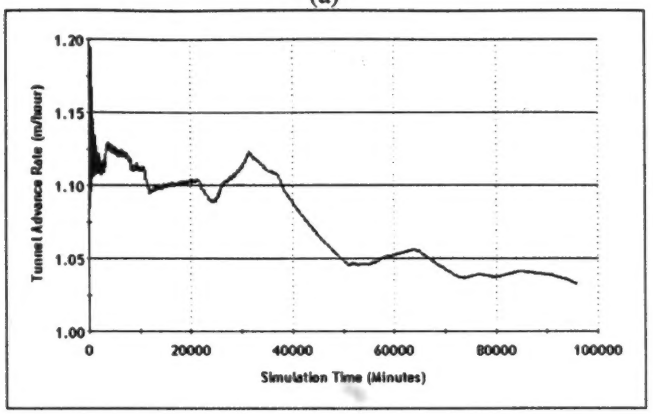
Figure 8-5: Productivity of the approximate models– (a) Model 1 (b) Model 2 and (c) Model 3 (Mill Woods Tunnel)

8.2.3 Results of the Mill Woods Case Study based on Soil Prediction Methods

Model 4, 5 and 6 were simulated using the soil prediction algorithms documented in Chapter 6. Figure 8.6 presents the tunnel advance rate for models 4 to 6. The productivity per shift for models 1 to 3 is shown in Figure 8-7. Model 4 uses boring rates calculated using the composition of the soils in each soil section based on the soil transition points. Composition is not deterministic throughout a soil segment in this case as compared to models 1 to 3. The values of the soil composition vary depending on the composition of the soils based on the soil transition points. Figure 8-8 shows a comparison of the rate of boring for soil section 12 using both model 3 (approximate compositions) and model 4 (based on soil transition points). The average boring rate for model 3 is 2.54 m/hour and the average boring rate for model 4 is 2.06 m/hour.

Although boring rates vary in some soil sections in the approximate method (model 3) and soil prediction method (model 4) using composition percentages of the soil, the overall productivity of model 4 of 9.12 m/hour is very similar to approximate models 1 to 3. The tunnel advance rate in Figure 8-6 (model 4) is somewhat different from the tunnel advance rate in Figure 8-4 (model 3) as model 4's tunnel advance rate has fluctuations based on the soil compositions. Figure 8-9 shows the difference in the pattern of the tunnel advance rate of model 3 and model 4. Figure 8-9 is divided into the 15 segments of the tunnel. Model 4 shows the fluctuation of the tunnel advance rate based on the soil transition points and the composition of the soil. The tunnel advance rate decreases when the composition of sandstone is increased. However, model 3 however does not show a pattern for the fluctuations in the tunnel advance rate.

(a)



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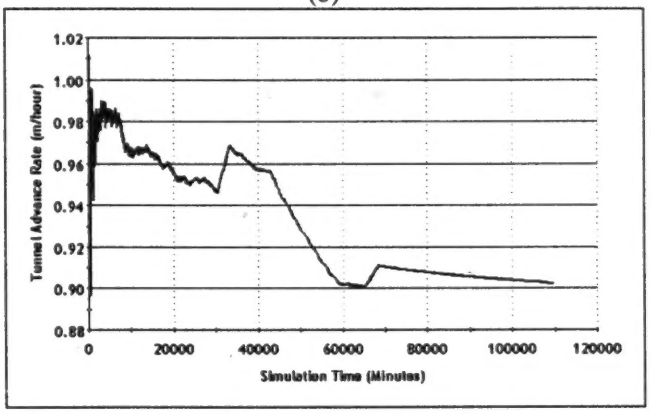


(c)

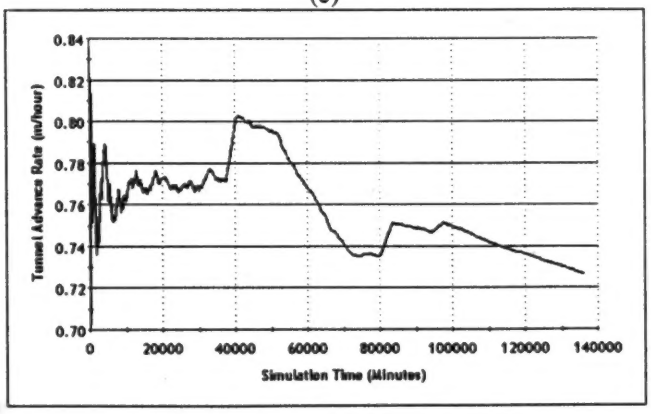


Figure 8-6: Tunnel Advance Rates of the Soil Transition models – Model 4 (b) Model 5 and (c) Model 6 (Mill Woods Tunnel)

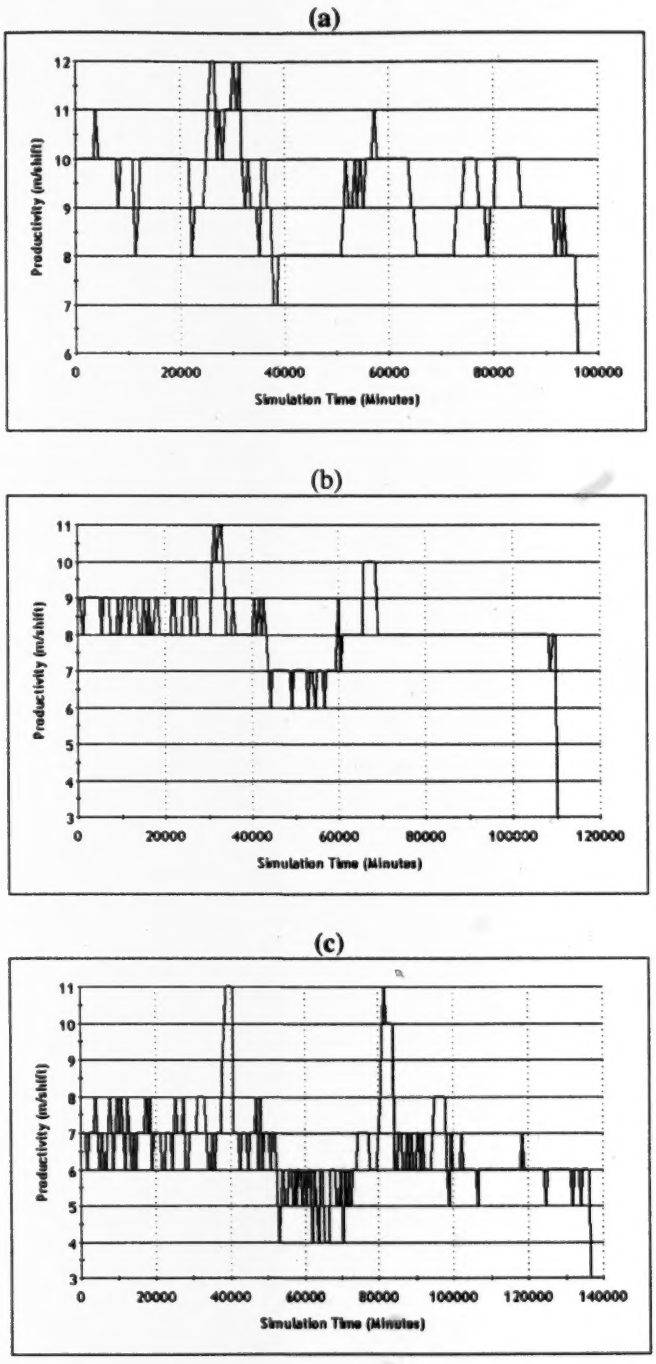
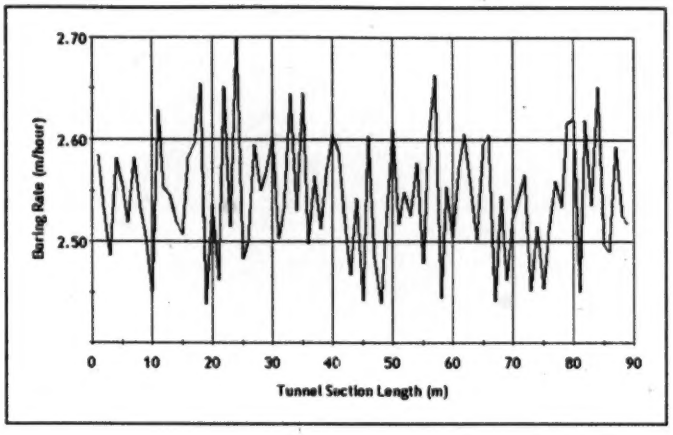


Figure 8-7: Tunnel Advance Rates of the Soil Transition models (a) Model 4 (b) Model 5 and (c) Model 6 (Mill Woods Tunnel)

(a)



(b)

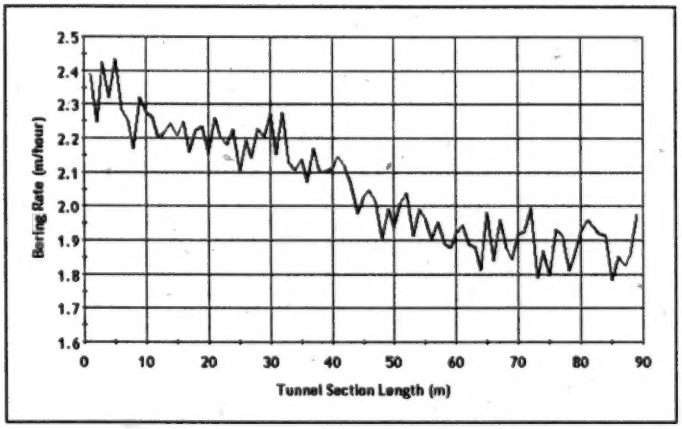


Figure 8-8: Comparison of the Boring Rates (a) Model 3 (b) Model 4

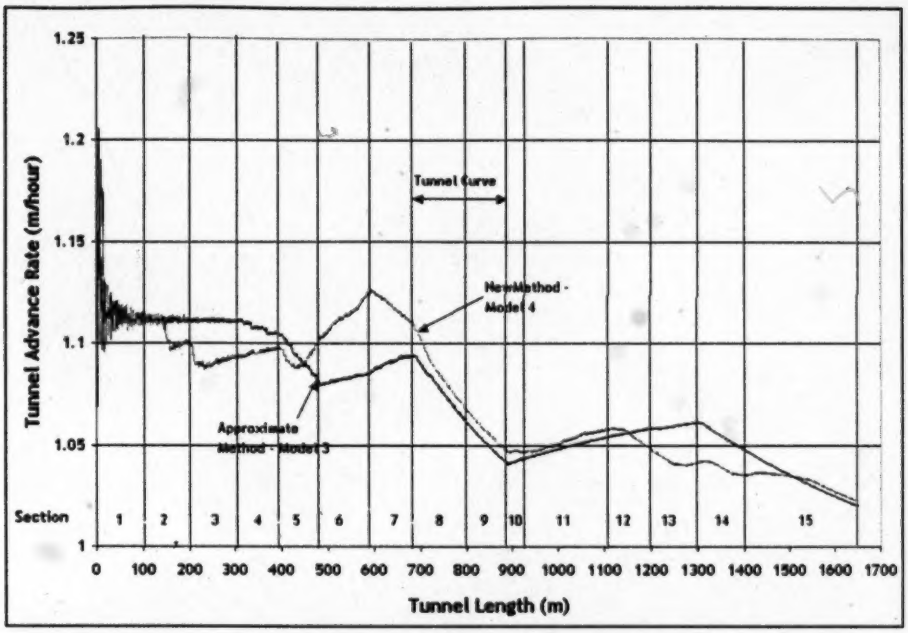


Figure 8-9: Comparison of the Tunnel Advance Rate (Approximate method – Model 3 Vs New Method – Model 4 based on the composition of soils)

Table 8-7 shows all the transition points from Model 4 based on 20 simulation runs. The last two columns of Table 8-7 depict the extent of the soils in each of the soil sections based on the average transition points. For example, in soil section 1, the entire 104 meters contains both shale and sandstone whereas only 26.20 meters contains the three layers (shale, sandstone, and shale). Within soil section 12, 34.60 of 89 meters contains both shale and sandstone whereas three soil layers never interact in this section. Shale and sandstone interact with each other for 1353 meters (82%) of 1651 meters of the tunnel. The rest of the 18% is either shale only or sandstone only. Further, 38.1% of the entire tunnel contains the mixture of shale and sandstone where one of the soils exists both above and below the other soil. These percentages demonstrate that the productivity heavily depends on the interaction of the two soils. 82% of the interaction is very high

and therefore selecting a proper method of boring rate prediction could have a great impact on the accuracy in productivity.

Table 8-7: Results generated from Model 4

Section	Length (m)	Top Transition (m)			Bottom Transition (m)			Extent of Two Layers (m)	Extent of Three Layers (m)
		Minimum	Average	Maximum	Minimum	Average	Maximum		
1	104	25.0	34.0	48.0	57.0	60.2	66.0	104.00	26.20
2	96	53.0	62.3	70.0	19.0	28.3	37.0	96.00	34.00
3	105	26.0	33.8	43.0				105.00	71.20
4	91	51.0	57.2	63.0				91.00	57.20
5	84	18.0	26.1	33.0				26.10	0.00
6	110				56.0	63.4	71.0	46.60	0.00
7	96				21.0	27.5	32.0	96.00	68.50
8	113	65.0	71.7	78.0				113.00	71.70
9	90	19.0	27.7	36.0				90.00	62.30
10	43	24.0	28.9	35.0				43.00	28.90
11	179	45.0	57.1	66.0	97.0	102.6	107.0	133.50	0.00
12	89	51.0	54.4	60.0				34.60	0.00
13	102				20.0	25.6	32.0	25.60	0.00
14	102	29.0	32.8	38.0	53.0	59.8	64.0	102.00	31.20
15	247				60.0	69.3	89.0	247.00	177.70
Total	1651							1353.40	628.90
							Percentage (%)	82.0%	38.1%

The boring rate was considered to be the worse of the two soils for model 5. Figure 8-6(b) provides the tunnel advance rate, which has fluctuations, based on the transition points. The boring rate of sandstone is the governing factor for productivity if tunnel excavation is performed in a mixture of shale and sandstone. As suggested by the tunnel supervisors, the most common scenarios for mixed phases of excavation is to assume that the productivity is worse than the minimum productivity of the two soils (model 6). Figure 8-6 (c) depicts the tunnel advance rate for model 6, which has the highest number of fluctuations in the tunnel advance rate from the tunnel start to the tunnel end. Since the final productivity of model 6 is very close to the actual productivity, Figure 8-10 is used

to compare the results of the actual and model 6's tunnel advance rates. Up to about the first 300 meters, the actual tunnel advance rate is far below the simulated tunnel advance rates. For the remainder of the tunnel, the actual tunnel advance rate is very close to the simulated tunnel advance rates. This comparison proves that the proper selection of inputs for boring rate could provide an accurate prediction of the tunnel productivity.

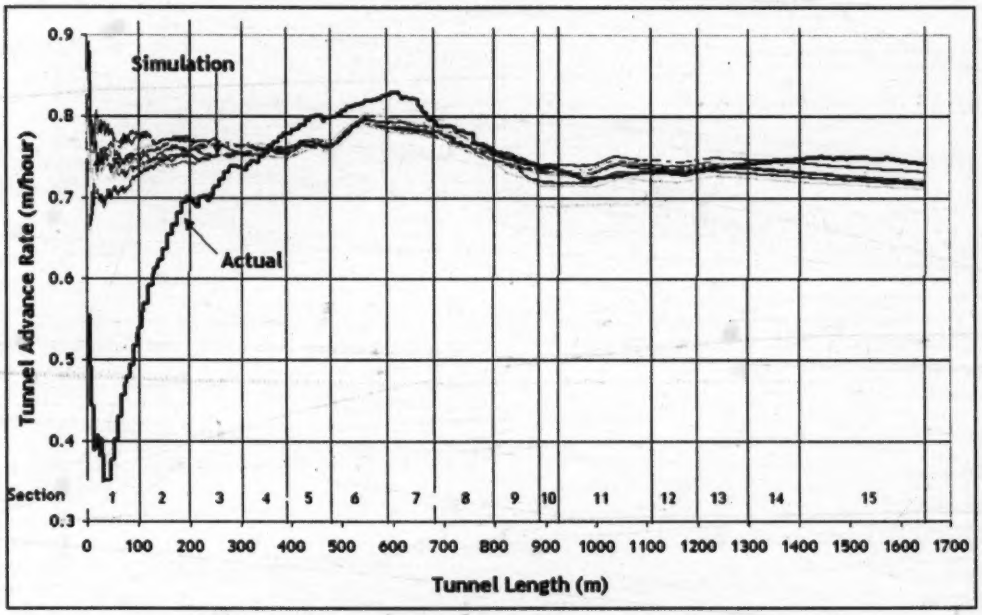


Figure 8-10: Tunnel Advance Rate – Actual Vs. Model 6

The tunnel advance rate (output) for 20 simulation runs are shown in Figure 8-10. A stochastic simulation does not produce the same output when simulated repeatedly with independent random seeds. According to Abourizk and Halpin (1991), a number of runs with independent seeds for the random number generating streams are required to ensure that a true picture of the system emerges. Typically, a simulator collects sample output from various runs conducted and then uses the sample as the basis for decision-making. Since the Simphony simulation engine uses independent seeds to generate

random numbers, building confidence intervals for the simulation would provide an acceptable interval for the simulation outputs. Given that the output are normally (or approximately normally) distributed, the procedure described by AbouRizk and Halpin (1991) may be used to construct these confidence interval around the mean of the data. Equation 8.1 provides an exact 100(1-α)% confidence interval for the mean.

$$\overline{X} \pm t_{(n-1),(1-\alpha/2)} \cdot \frac{S}{\sqrt{n}} \quad \text{.....(8.1)}$$

In equation 8.1, n is the number of simulation runs, $\overline{X}$ is the mean of the output (mean advance rate for each tunnel meter), $t_{(n-1),(1-\alpha/2)}$ is the upper 1 - α/2 point of the t-distribution with (n-1) degrees of freedom, S is the standard deviation of the outputs, and (1-α/2) is the confidence level desired. Figure 8-11 shows interval of the tunnel advance rate for model 6 at 95% confidence level for 25 simulation runs.

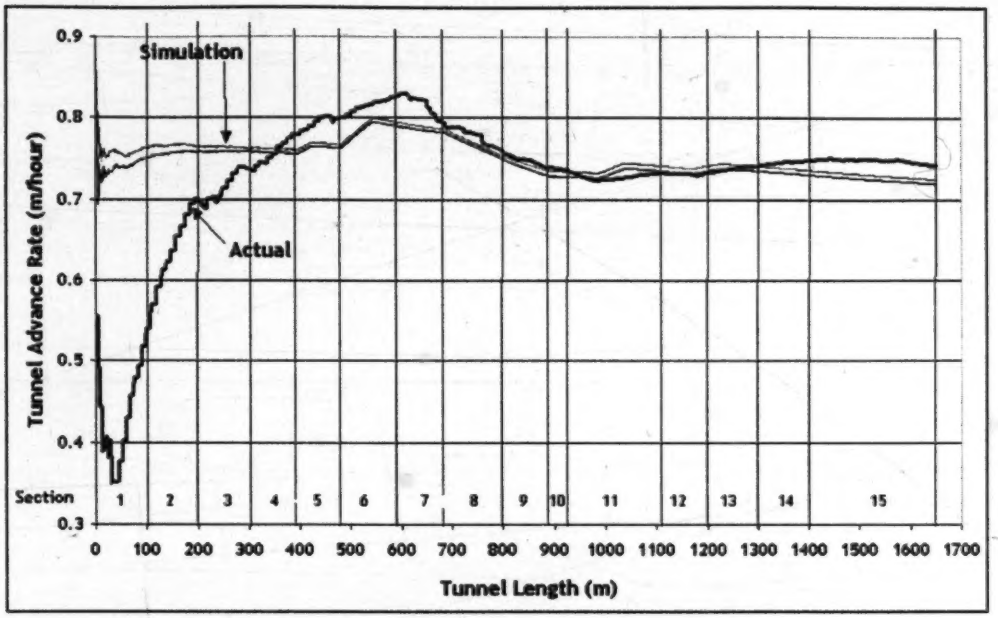


Figure 8-11: Tunnel Advance Rate – Actual Vs. Model 6 (with 95% confidence)

Figure 8-11 shows that the actual tunnel advance rate is within the 95% confidence interval of the mean of the tunnel advance rate from the 25 simulation runs after 350 meters from the tunnel start where the difference between the actual tunnel advance rate and the confidence interval is as low as 0.00005 meters/hour. During the first 350 meters, it is not possible to justify the reason for a very low tunnel advance rate and neither the tunnel log reports nor the expertise obtained from the tunnel personnel could provide justification. Further, the reliability of the data was questionable.

8.3 Conclusions

The validation in this chapter provides an application of the modeling algorithms and simulation discussed in Chapters 6 and 7 to a past tunnel construction project. The new

modeling algorithms to predict the soil transition provide the following benefits. The following were also evident from the case study presented in the chapter.

1 The modeling algorithms implemented within special purpose simulation provide an analytical approach to predict the transition points along the tunnel path and thereby to determine the tunnel production rate, rather than applying the approximate production rates based on the arbitrary/approximate composition of the soils.

2 If the boring rate is based on the composition of the soils, the new method provides a better picture of the overall tunnel project that allows engineers and managers to make decisions and to take remedial action (if any) before construction commences.

3 Since the mixed soil phases are quite common in tunnel construction operations, the proper input of the boring rate will provide an accurate production rate for tunneling. In the case study, the actual tunnel productivity (despite the reliability of the data) was almost predicted through simulation by applying a boring rate for mixed soil phases.

4 The new modeling algorithm not only provided a logical approach to predict the productivity based on the transition of soils, but also an accurate prediction assuming that the end user selects the proper input data.

The successful development and application of the soil transition modeling algorithms reduce the risk and uncertainty in predicting the tunnel advance rate and productivity. The application of these algorithms within special purpose simulation to future tunnel construction projects will allow better project planning and decision-making for the engineers before the actual construction commences.

Chapter 9: Conclusions and Recommendations

9.1 Research Summary

This thesis presented the design, development, and successful implementation of a solution to a real and complex construction process using special purpose simulation. Utility tunnel construction is the application domain of this special purpose simulation. The development of this simulation tool is a result of independent course work in simulating tunnel construction work, the birth of a flexible and a powerful simulation engine called Simphony, and the successful collaborative research work between the City of Edmonton Asset Management and Public Works Department and the NSERC/Alberta Construction Industry Research Chair in Construction Engineering and Management. The research presented in the thesis can be divided into three phases.

The first phase of the research focused on developing a special purpose simulation template for utility construction operations using Simphony as construction simulation is a great tool for decision makers and planners in analyzing various construction operations and alternatives. The actual tunnel construction processes at the City of Edmonton Asset Management and Public Works Department was studied before creating this tool. The success of the development of the tunnel simulation template was the collaborative research approach adopted by the developer with the City of Edmonton and the flexibility and user friendliness included in the template. A non-simulation expert who is familiar with tunneling is able to create and use this tool without the assistance of the developer. The tunnel template was tested and validated and then applied for the pre-project

planning and bidding analysis of two tunnel construction projects in Edmonton. During the application of the tunnel template, several critical factors were identified to predict the accuracy and to reduce the uncertainty in tunneling. Prediction of soil type was identified as the most critical factor to perform additional research that could contribute to make the tunnel simulation more accurate and thereby to curtail the risk and uncertainty in tunnel construction projects. Further, this simulation tool allowed the engineers and managers of the City of Edmonton to explore alternative options to construct the tunnels.

The second phase of the research was the successful development of an analytical methodology to predict the probability of soil types and soil families along the tunnel path for construction purposes. The geological conditions in Edmonton were studied to develop the methodology. This part of the research produces an analytical method to define and characterize the main soil types in the area and to predict the probability of existence of soil types and the soil profiles along the tunnel path. The prediction of soil types and families, which also consider the co-existence of a soil with other soil types, provides a novel approach that can be beneficial to the engineers at the pre-project planning of tunnel construction project. The transition from one family of soil to another provided the background information for the development of the third phase of research.

The third phase of the research focused on developing several modeling algorithm modules to predict the transitions of soils during tunneling in the tunnel path. The developed soil transition algorithms were then incorporated within the special purpose tunnel simulation template to make simulation more accurate for the decision makers. The use of transitional probabilities based on Markov theory helped to generate the soil

transition points along the tunnel path based on the soil profiles in the boreholes. The rate of boring and the productivity were based on the transition points and the composition of the soils. An end-user who is familiar with tunneling could determine the best scenario by applying the productivity values based on the composition of the soils, minimum boring rate of the soils or worse than the minimum boring rate when tunneling in mixed soils. The validation of a hypothetical tunnel project showed that this modeling approach is better than the approximate method used in the first phase of the research, resulting in better project planning and decision-making.

9.2 Summary of Research Contributions

This thesis research has led to numerous contributions to construction simulation, tunnel construction operations, and prediction of soil types for tunneling. These contributions contain a mixture of new methods and improvements to the current practices.

Developing a flexible special purpose simulation for tunnel construction operations is a major contribution to construction simulation. The use of a flexible modeling approach based on the construction sequence enables end-users who are not familiar with simulation, but have expertise in tunneling, to create a model and experiment by changing the parameter values in the modeling elements. The design of graphical modeling elements enabled the end users to develop a model with ease. The adaptability of hypothetical work conditions such as breaks for lunches and end of shifts provided a true picture of a real system. This SPS tool became very useful because of the cost-planning engine that is built within Simphony, to produce the cost, schedule, productivity, cash flow, and resource utilization based on the simulation results. The

ability to model for several scenarios without changing the developer's code or the base of the tool is another advantage of this tool.

The successful implementation of this tool enabled the industry personnel to adopt it for the project management of a tunnel project in the areas of project planning, bidding analysis, optimizations, resource selection, construction method selection, alternate planning, and productivity improvements. The use of the cost planning module assisted the planners, engineers and estimators to prepare a preliminary estimate of a tunnel construction project for evaluating several scenarios of project planning and bidding analysis. Further, this tool allowed industry practitioners to believe in the practical benefits of simulation, which is usually not typically embraced by industry due to its strong academic nature. The successful implementation of the simulation for actual construction projects motivated the further opportunities to conduct collaborative research work to assist their production process. The development of this tool opened various avenues for the industry personnel to demand additional embellishments for modeling various alternatives.

The prediction of soil types and soil families along the tunnel path is a new analytical methodology that assists the planners and engineers during pre-project planning of tunnel construction projects. This method is presented for construction engineers or managers to analyze the soil types along the tunnel path independent of the typical geological exploration conducted for the project. This method will enable the planners, engineers, and managers to justify the geological prediction and borehole explorations performed for the project and to make additional judgments before actual construction commences. In summary, this analysis defines and characterizes the soil

types using soil clusters and soil families, predict the existence of a soil, predict the co-existence of a soil with other soils under different clusters, predict the existence of a soil behaviour and then predict the soil families along the tunnel path. The use of this analysis for hypothetical tunnel construction will reduce the uncertainty of the project by logically investigating the soil types in the tunneling path before commencing actual construction. Although the application of this method was limited to Edmonton geology, the method can be used for any other city or area provided that the city or area has adequate published data or borehole data from the past tunnel construction projects.

The last major contribution is the development of soil prediction algorithm modules when soil types interact with each other to predict the soil transition points. The soil prediction modules were then incorporated within the SPS tunnel template without losing the originality of the tunnel template. With this new approach, the end users can specify the borehole data rather than approximating soil data for a specific section of a tunnel. Based on the inputted soil data and the user inputs, SPS template determines the best modeling scenario between the two boreholes and predicts soil transition points and productivity values. This method also enables the end users to specify the calculation method for the rate of boring for production purposes. The productivity of the tunnel is determined through an analytical method based on the soil transition points along the tunnel. The validated case study proved that these modeling algorithms not only provide a logical approach to predict the productivity based on the transition of soils, but also an accurate prediction given the fact that the end user inputs the actual data.

9.3 Recommendations for Future Research and Development

During the design, development and implementation stages of the SPS tunnel template, the following have been noted as recommendations for further research and development to improve tunnel construction operations and construction simulation in general.

1. The success of the simulation depends on proper application and validation. The lack of proper data was evident throughout the entire process. It is recommended that collection of data for tunnel construction operations be encouraged in order to create a sound database. A detailed input modeling and output analysis could be performed based on the data collection. The use of logical statistical distributions for activity durations could provide more meaningful results for tunnel simulation.
2. Figure 4.10 of Chapter 4 shows that tunnel productivity depends on many quantitative and qualitative factors. The inclusion of qualitative factors within the SPS could allow better inputs and thereby generate logical outputs. Humans inherently think and reason in qualitative terms. Even though a simulation model is quantitative, a better method for man-machine interfaces, and the translation methods from qualitative to quantitative knowledge and vice versa, are required. It is recommended to add qualitative simulation approaches that could augment traditional quantitative approaches by making them more amenable to a wide range of simulation users with different levels of expertise, in both simulation methodology and the problem domain, as supported by Fishwick (1991).
3. There are many uncertain factors that affect the tunnel construction. This includes the prediction of equipment breakdown, repair and maintenance, efficiency of the TBM, labour efficiency and breaks, encountering of water during tunneling, etc. The proper

collection of data could help to determine the occurrence of these events. It is recommended to add these uncertainties to make the tunnel template more flexible and accurate.

4. The Simphony modeling engine employs discrete event simulation. In the developed tunnel template, continuous simulation methods were adopted on an ad-hoc basis to model the suspension of work for lunches and at the end of the shifts. The proper inclusion of the continuous simulation methodology within Simphony would allow better modeling flexibility to a developer. Hence, it is recommended to develop a combined discrete event and continuous simulation framework to produce more beneficial SPS tools for various construction operations.
5. During the study, it was revealed that the industry would prefer to use the same construction method, sequence, and schedule for the work. The use of two-way tunneling for a tunnel construction project was justified through simulation. It is then recommended that the tunnel construction methods, work sequencing, resource selections should be thoroughly studied to identify whether those processes can be executed differently to obtain better efficiency. Simulation could assist in making decisions to support these new alternatives.
6. The prediction of soils and soil families could be extended to further advanced levels. The present study limits the prediction to major soil types. However, there are various minor soil types within a major soil category. For example, shale, clayshale, sandstone, bentonite, and siltstone are within the bedrock major category. The prediction of these individual soil types along a tunnel path could provide better

inputs for the simulation model. It is recommended to extend this soil prediction study for minor soil types to predict the probability of its existence and the elevations.

7. A soil has various properties such as plasticity, moisture content, compressive strength, granularity, etc., and the rate of boring would differ based on the properties of soils. It is recommended to study these properties and develop an analytical model that could be added to the SPS tunnel template to derive boring rates.
8. As discussed in Section 6.5, further analysis is recommended to identify variations of the various scenarios depicted in Tables 6.4 and 6.5. This analysis will identify any changes in the soil profiles that may be possible between the boreholes to predict the soil transitions between the boreholes.

The successful development and implementation of these tools will provide a more comprehensive tunnel simulation template that could be very beneficial to academia and the industry.

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APPENDIX "A ": TERMINOLOGY USED IN CHAPTER 5

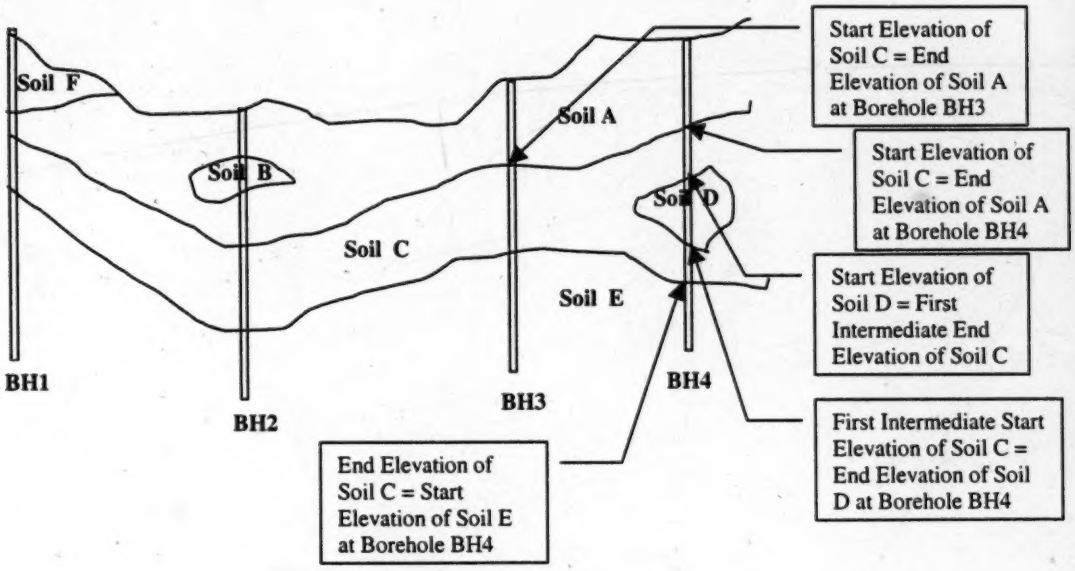

Soil F
Soil B
Soil C
Soil A
Soil D
Soil E
BH1
BH2
BH3
BH4
Start Elevation of Soil C = End Elevation of Soil A at Borehole BH3
Start Elevation of Soil C = End Elevation of Soil A at Borehole BH4
Start Elevation of Soil D = First Intermediate End Elevation of Soil C
First Intermediate Start Elevation of Soil C = End Elevation of Soil D at Borehole BH4
End Elevation of Soil C = Start Elevation of Soil E at Borehole BH4

Figure A-1: Soil Layers with Boreholes

Figure A-1 is used to explain the various terms used in Chapter 5. There are six soil layers. BH1 to BH4 are boreholes in Figure A-1.

Elevation: Height of a soil layer above the mean sea level.

Thickness: This is the vertical distance between the End Elevation of a soil layer and the Start Elevation of the same soil layer at a particular point (or borehole). The thicknesses of a Soil layer which is not continuous vertically (soil C in Borehole BH4) are calculated separately. The thickness of soil layer C above soil layer D is the vertical distance between the Start Elevation of soil layer C and the First Intermediate End Elevation of

soil C at Borehole BH4. The thickness of soil layer C below soil layer D is the vertical distance between the First Intermediate Start Elevation for Soil Layer C and the End Elevation of Soil Layer C at Borehole BH4.

A Continuous Soil Layer: A soil layer that spans across the boreholes continuously. Soil Layers A, C, and E are continuous soil layers.

A Soil Pocket (non-continuous Soil Layer): A soil layer that does not span across boreholes continuously. Soil B and soil E are soil pockets. Soil F does not meet the definition of a soil pocket as the stratigraphy to the borehole BH1 is not known.

Surficial Soil Type: The first soil layer that can be found on the surface or ground at any point. For example, there are two surficial soil types in Figure A-1. Soil F is the surficial soil at BH1. Soil A is the surficial soil at BH2, BH3, and BH4.

Soil Family: A Soil Family is the order of the different soil types that exist vertically at discrete elevations commencing from the surficial soil to the bottommost layer at a given point within an area. There are four separate families in the boreholes in to Figure A-1. BH1 has a family of soil F, soil B, soil C, and soil E. The notation of this soil family is either given as FBCE or F-B-C-E. On the same basis, BH2 has soil family ABACE, BH3 has ACE and BH4 has ACDCE.

APPENDIX "B": Borehole Details – All Clusters

Table B1: Borehole Details starting from Soil Type 5

Percentage	Total Number	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5
64.29%	18	5	1			
7.14%	2	5	6	5	1	
7.14%	2	5	3	1		
3.57%	1	5	8	9	5	1
3.57%	1	5	8	5	3	1
3.57%	1	5	8	5	1	
3.57%	1	5	6	5	3	1
3.57%	1	5	6	1		
3.57%	1	5	4	5	1	
100.00%	**28**					

Table B2: Borehole Details starting from Soil Type 6

Percentage	Total Number	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6
50.00%	3	6	5	1			
16.67%	1	6	8	6	5	3	1
16.67%	1	6	5	6	1		
16.67%	1	6	1				
100.00%	**6**						

Table B3: Borehole Details starting from Soil Type 7

Percentage	Total Number	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6
40.00%	14	7	5	1			
14.29%	5	7	5	6	5	1	
11.43%	4	7	5	3	1		
11.43%	4	7	5	2	5	1	
8.57%	3	7	6	5	1		
2.86%	1	7	8	5	1		
2.86%	1	7	8	3	1		
2.86%	1	7	6	5	2	5	1
2.86%	1	7	5	6	5	3	1
2.86%	1	7	5	6	1		
100.00%	**35**						

Table B4: Borehole Details starting from Soil Type 8

Percentage	Total Number	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6	Layer 7	Layer 8	Layer 9
34.80%	79	8	5	1						
33.48%	76	8	5	3	1					
3.96%	9	8	5	6	5	1				
3.08%	7	8	7	5	1					
2.64%	6	8	5	2	5	1				
2.64%	6	8	5	6	5	3	1			
2.20%	5	8	5	6	1					
1.76%	4	8	7	5	3	1				
1.76%	4	8	5	2	3	1				
1.76%	4	8	9	1						
1.76%	4	8	6	5	3	1				
1.32%	3	8	9	5	3	1				
1.32%	3	8	1							
0.44%	1	8	5	4	5	1				
0.44%	1	8	5	6	5	2	3	1		
0.44%	1	8	5	3	5	1				
0.44%	1	8	5	2	5	3	1			
0.44%	1	8	5	3	5	3	1			
0.44%	1	8	5	6	5	2	5	1		
0.44%	1	8	6	1						
0.44%	1	8	9	8	9	5	1			
0.44%	1	8	6	5	1					
0.44%	1	8	7	5	2	5	1			
0.44%	1	8	7	5	6	1				
0.44%	1	8	7	5	6	5	1			
0.44%	1	8	7	6	1					
0.44%	1	8	7	8	5	1				
0.44%	1	8	9	5	1					
0.44%	1	8	9	5	6	5	3	1		
0.44%	1	8	5	6	5	6	5	2	3	1
100.00%	227									

Table B5: Borehole Details starting from Soil Type 9

Percentage	Total Number	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6	Layer 7
100.00%	1	9	8	9	5	6	5	1

Table B6: Borehole Details starting from Soil Type 10

Percentage	Total Number	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5
100.00%	1	10	9	8	5	1

Table B7: Borehole Details starting from Soil Type 11

Percentage	Total Number	Layer 1	Layer 2
100.00%	2	11	1

APPENDIX "C": P_{CL} Values of Soils Within All Clusters

Table C1: Calculation of Probability of a Soil type 2 within all Clusters

Soil Type 2

Cluster $_i$	P_{CL} Value ($P_{CL\,i}$)	N (2) $_i$	Total (T_i)	N (2) $_i$/T_i	$P_{CL\,i} \times$N (2) $_i$/T_i
5	0.09333	0	9	0	0
6	0.02000	0	4	0	0
7	0.11667	2	10	0.2	0.0233
8	0.75667	7	30	0.2333	0.1766
9	0.00333	0	1	0	0
10	0.00333	0	1	0	0
11	0.00667	0	1	0	0

PC[2] **0.1999**

Table C2: Calculation of Probability of a Soil type 3 within all Clusters

Soil Type 3

Cluster $_i$	P_{CL} Value ($P_{CL\,i}$)	N (3) $_i$	Total (T_i)	N (3) $_i$/T_i	$P_{CL\,i} \times$N (3) $_i$/T_i
5	0.09333	3	9	0.3333	0.0311
6	0.02000	1	4	0.25	0.005
7	0.11667	3	10	0.3	0.035
8	0.75667	12	30	0.4	0.3027
9	0.00333	0	1	0	0
10	0.00333	0	1	0	0
11	0.00667	0	1	0	0

PC[3] **0.3738**

Table C3: Calculation of Probability of a Soil type 4 within all Clusters

Soil Type 4

Cluster $_i$	P_{CL} Value ($P_{CL\ i}$)	N (4) $_i$	Total (T_i)	N(4) $_i$/T_i	$P_{CL\ i} \times$N (4) $_i$/T_i
5	0.09333	1	9	0.1111	0.0104
6	0.02000	0	4	0	0
7	0.11667	0	10	0	0
8	0.75667	1	30	0.0333	0.0252
9	0.00333	0	1	0	0
10	0.00333	0	1	0	0
11	0.00667	0	1	0	0

PC[4] **0.0356**

Table C4: Calculation of Probability of a Soil type 5 within all Clusters

Soil Type 5

Cluster $_i$	P_{CL} Value ($P_{CL\ i}$)	N(5) $_i$	Total (T_i)	N(5) $_i$/T_i	$P_{CL\ i} \times$N (5) $_i$/T_i
5	0.09333	9	9	1	0.0933
6	0.02000	3	4	0.75	0.015
7	0.11667	9	10	0.9	0.105
8	0.75667	26	30	0.8667	0.6558
9	0.00333	1	1	1	0.0033
10	0.00333	1	1	1	0.0033
11	0.00667	0	1	0	0

PC[5] **0.8758**

Table C5: Calculation of Probability of a Soil type 6 within all Clusters

Soil Type 6

Cluster $_i$	P_{CL} Value ($P_{CL\ i}$)	N (6) $_i$	Total (T_i)	N(6) $_i$/T_i	$P_{CL\ i} \times$N (6) $_i$/T_i
5	0.09333	3	9	0.3333	0.0311
6	0.02000	4	4	1	0.02
7	0.11667	5	10	0.5	0.0583
8	0.75667	13	30	0.4333	0.3279
9	0.00333	1	1	1	0.0033
10	0.00333	0	1	0	0
11	0.00667	0	1	0	0

PC[6] **0.4407**

Table C6: Calculation of Probability of a Soil type 7 within all Clusters

Soil Type 7

Cluster $_i$	P_{CL} Value ($P_{CL\ i}$)	N (7) $_i$	Total (T_i)	N(7) $_i$/T_i	$P_{CL\ i} \times$N (7) $_i$/T_i
5	0.09333	0	9	0	0
6	0.02000	0	4	0	0
7	0.11667	10	10	1	0.1167
8	0.75667	7	30	0.2333	0.1766
9	0.00333	0	1	0	0
10	0.00333	0	1	0	0
11	0.00667	0	1	0	0

PC[7] **0.2932**

Table C7: Calculation of Probability of a Soil type 8 within all Clusters

Soil Type 8

Cluster $_i$	P_{CL} Value ($P_{CL\,i}$)	N (8) $_i$	Total (T_i)	N(8) $_i/T_i$	$P_{CL\,i} \times$N (8) $_i/T_i$
5	0.09333	3	9	0.3333	0.0311
6	0.02000	1	4	0.25	0.005
7	0.11667	2	10	0.2	0.0233
8	0.75667	30	30	1	0.7567
9	0.00333	1	1	1	0.0033
10	0.00333	1	1	1	0.0033
11	0.00667	0	1	0	0

PC[8] **0.8228**

Table C8: Calculation of Probability of a Soil type 9 within all Clusters

Soil Type 9

Cluster $_i$	P_{CL} Value ($P_{CL\,i}$)	N (9) $_i$	Total (T_i)	N(9) $_i/T_i$	$P_{CL\,i} \times$N (9) $_i/T_i$
5	0.09333	1	9	0.1111	0.0104
6	0.02000	0	4	0	0
7	0.11667	0	10	0	0
8	0.75667	5	30	0.1667	0.1261
9	0.00333	1	1	1	0.0033
10	0.00333	1	1	1	0.0033
11	0.00667	0	1	0	0

PC[9] **0.1431**

Table C9: Calculation of Probability of a Soil type 10 within all Clusters

Soil Type
10

Cluster $_i$	P_{CL} Value ($P_{CL\,i}$)	N (10) $_i$	Total (T_i)	N(10) $_i$/T_i	$P_{CL\,i} \times$N (10) $_i$/T_i
5	0.09333	0	9	0	0
6	0.02000	0	4	0	0
7	0.11667	0	10	0	0
8	0.75667	0	30	0	0
9	0.00333	0	1	0	0
10	0.00333	1	1	1	0.0033
11	0.00667	0	1	0	0

PC[10] **0.0033**

Table C10: Calculation of Probability of a Soil type 11 within all Clusters

Soil Type
11

Cluster $_i$	P_{CL} Value ($P_{CL\,i}$)	N (11) $_i$	Total (T_i)	N (11) $_i$/T_i	$P_{CL\,i} \times$N (11) $_i$/T_i
5	0.09333	0	9	0	0
6	0.02000	0	4	0	0
7	0.11667	0	10	0	0
8	0.75667	0	30	0	0
9	0.00333	0	1	0	0
10	0.00333	0	1	0	0
11	0.00667	1	1	1	0.0067

PC[11] **0.0067**

APPENDIX "D": SOIL FAMILIES

Soil Family of the Previous Borehole	Soil Family of the Present Borehole	Soil Family of the Next Borehole
51	51	51
51	51	51
51	51	51
51	51	5651
51	51	5651
51	51	651
51	51	7531
51	51	75651
51	51	75651
51	51	851
531	51	51
531	51	531
5851	51	51
5851	51	7531
651	51	51
651	51	751
751	51	51
751	51	51
751	51	51
751	51	51
751	51	751
751	51	751
75651	51	751
75651	51	851
851	51	686531
8531	51	51
8531	51	81
51	651	751
5651	651	51
75651	651	751
75651	651	85651
51	751	51
51	751	751
51	751	75251
51	751	851

Soil Family of the Previous Borehole	Soil Family of the Present Borehole	Soil Family of the Next Borehole
651	751	51
751	751	51
751	751	51
751	751	686531
751	751	75651
751	751	756531
75251	751	75651
75251	751	756531
7531	751	531
75651	751	751
75651	751	751
756531	751	751
756531	751	751
7851	751	851
7851	751	852531
851	751	51
851	751	751
851	751	75251
851	751	7561
851	751	851
851	751	851
85651	751	851
8751	751	51
8751	751	7561
751	7561	75651
51	75651	51
51	75651	651
51	75651	75251
5651	75651	651
751	75651	5651
7561	75651	651
7561	75651	75251
85651	75651	751
109851	851	58951
51	851	751
5451	851	751
561	851	56531
751	851	51
751	851	5651

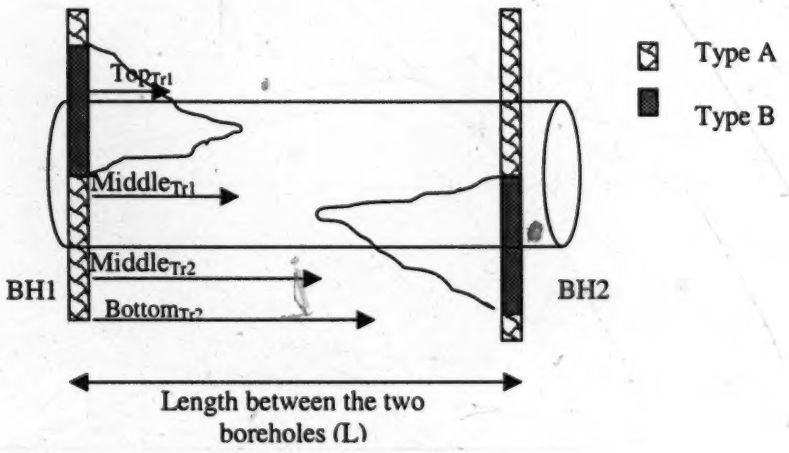
Soil Family of the Previous Borehole	Soil Family of the Present Borehole	Soil Family of the Next Borehole
751	851	8531
751	851	85651
751	851	85651
7531	851	8561
81	851	81
81	851	851
851	851	5451
851	851	7851
851	851	851
851	851	851
851	851

Soil Family of the Previous Borehole	Soil Family of the Present Borehole	Soil Family of the Next Borehole
851	851	8531
851	851	8531
851	851	8531
851	851	8531
851	851	85651
851	851	85651
851	851	85651
851	851	85651
851	851	85651
851	851	8651
851	851	8751
851	851	89531
85231	851	851
85231	851	85651
85251	851	851
85251	851	85251
85251	851	8531
85251	851	85651
8531	851	751
8531	851	851
8531	851	851
8531	851	851
8531	851	851
8531	851	851
8531	851	851
8531	851	85251
8531	851	8531
8531	851	8531
8531	851	8531
8531	851	8531
8531	851	8531
8531	851	85351
8561	851	851
85651	851	851
85651	851	851
85651	851	8531
85651	851	8531
85651	851	8531
856531	851	851

Soil Family of the Previous Borehole	Soil Family of the Present Borehole	Soil Family of the Next Borehole
856531	851	8531
861	851	5451
861	851	851
8651	851	51
8651	851	85651
875251	851	8761
87561	851	8531
87851	851	851
87851	851	8531
891	851	851
891	851	85231
89531	851	87851
651	85651	751
651	85651	75651
851	85651	751
851	85651	75651
851	85651	7651
851	85651	851
851	85651	851
851	85651	851
851	85651	851
851	85651	8531
851	85651	8531
851	85651	86531
8531	85651	85251
8565251	85651	8531
89531	85651	851

APPENDIX "E": Modeling Algorithms for Additional Scenarios

TRANSITION OF SOILS BOTH AT TOP AND BOTTOM ELEVATIONS WITH INTERMEDIATE SOIL POCKETS (FIGURE 6-12 AND SCENARIO 111 IN TABLE 6-6)



This scenario involves one transition point at the top elevation and one at the bottom elevation and two transitions in the middle. At the top elevation, transition is from Soil B to Soil A. At the bottom elevation, transition is from Soil A to Soil B. At the center of the tunnel thickness, the first transition is from Soil B to Soil A and then from Soil B to Soil A. The following are the steps in calculating the transition points, and the composition of soils.

Calculation of Transition Points

1. Generate random numbers between 0 and 1 equal to the length between the two boreholes (Random numbers L times)
2. Arrange the random numbers in a descending order with an assigned index number for each random number
3. Use the following algorithm to determine whether the random number belongs to soil A or soil B. If the transition is from Soil B to A, the transitional probability of $P_{Top}(B/A)$ is the decision-making threshold value. If the transition is from Soil A to B, the transitional probability of $P_{Top}(A/B)$ is the decision making threshold value.

   Random Number <= $P_{Top}(B/A)$ ⟶ *Soil A*

   Random Number > $P_{Top}(B/A)$ ⟶ *Soil B*

4. Identify the index number, which changes from Soil B to A. This index number is the top transition length (Top_{Tr1}) from Borehole BH1.
5. Re-generate random numbers between 0 and 1 equal to the equal to the length between the two boreholes (Random numbers L times).
6. Arrange the random numbers in a descending order with an assigned index number for each random number.
7. Use the same algorithm to determine whether the random number belongs to soil A or soil B to find out the first transition point of the pocket at the middle portion of the tunnel.

   Random Number <= $P_{Center}(B/A)$ ⟶ *Soil A*

   Random Number > $P_{Center}(B/A)$ ⟶ *Soil B*

8. Identify the index number, which change from Soil B to A. The index number is the first middle transition length from BH1.
9. Then re-generate random numbers between 0 and 1 equal to the equal to the first middle transition point and BH2 ($L - Center_{Tr1}$).
10. Arrange the random numbers in a descending order with an assigned index number for each random number.
11. Use the same algorithm to determine whether the random number belongs to soil A or soil B to find out the second middle transition point.

$$Random\ Number <= P_{Center}(A/B) \longrightarrow Soil\ B$$

$$Random\ Number > P_{Center}(A/B) \longrightarrow Soil\ A$$

12. Identify the index number, which changes from Soil A to B. The index number is the length from the first middle transition point.
13. Re-generate random numbers between 0 and 1 equal to the equal to the length between second middle transition point and BH2.
14. Arrange the random numbers in a descending order with an assigned index number for each random number.
15. Use the same algorithm to determine whether the random number belongs to soil A or soil B to find out the transition point of the pocket at the bottom elevation of the tunnel.

$$Random\ Number <= P_{Bottom}(A/B) \longrightarrow Soil\ B$$

$$Random\ Number > P_{Bottom}(A/B) \longrightarrow Soil\ A$$

16. Identify the index number, which change from Soil A to B. The index number is length between the 2nd middle transition point and BH2.

Calculation of the Composition of Soil and the profile of the Transition Curve

Soil section between the two boreholes is divided into five segments to calculate the composition of soils; BH1 to top transition point, top transition point to first middle transition point, first middle transition point to second middle transition point, second middle transition point to bottom transition point, and bottom transition point to BH2.

i. Start Elevation of Soil B at BH1 = SE_{BH1} (B)

ii. Start Elevation of Soil B at BH2 = SE_{BH2} (B)

iii. Finish Elevation of Soil B at BH1 = EE_{BH1} (B)

iv. Finish Elevation of Soil B at BH2 = EE_{BH2} (B)

v. Top Elevation of the BH1 = TE_{BH1}

vi. Bottom Elevation of the BH1 = EE_{BH1}

vii. Top Elevation of the BH2 = TE_{BH2}

viii. Bottom Elevation of the BH2 = EE_{BH2}

ix. Top Transition Distance from BH1 = LTR_{Top}

x. Bottom Transition Distance from BH1 = LTR_{Bottom}

xi. First Middle Transition Distance from BH1 = $LTR_{Middle1}$

xii. Second Middle Transition Distance from BH1 = $LTR_{Middle2}$

xiii. Composition of Soil A at Point $_i$ = Comp(A) $_i$

xiv. Composition of Soil B at Point i = Comp(B) $_i$

xv. Random Number at Point i = Rnd# $_I$

xvi. Depth of the Tunnel = D

Two random numbers are generated to identify the depth of the middle transition point from the top elevation and the depth of the middle transition point from the bottom elevation.

Elevation of the Middle Transition Point1 (EM1)= $TE_{BH1} - Rnd\,\# \times (TE_{BH1} - EE_{BH1}(B))$

Elevation of the Middle Transition Point2 (EM2)= $EE_{BH2} + Rnd\,\# \times (SE_{BH2}(B) - EE_{BH2})$

Two temporary elevations for the Soil B pockets are required (TempE1 for Pocket 1; and TempE2 for Pocket2).

$$TempE1 = EM1 - \left[\frac{LTR_{Middle1} - LTR_{Top}}{LTR_{Middle1}} \times (EM1 - EE_{BH1}(B))\right]$$

$$TempE2 = EM2 + \left[\frac{LTR_{Bottom} - LTR_{Middle2}}{L - LTR_{Middle2}} \times (SE_{BH2}(B) - EM2)\right]$$

BH1 to Top Transition Point

a) Generate random numbers from 0 to 1 equal to the distance of LTR_{Top}

b) Arrange them in a ascending order with an assigned index number (i = 1 to LTR_{Top} for each random number)

c) Calculate the composition using the formula

$$Comp(B)_i = Rnd\#_i \times \left[\frac{TempE1 - EE_{BH1}(B)}{D}\right] + \left[\frac{TE_{BH1}(B) - TempE1}{D}\right]$$

$$Comp(A)_i = 1 - Comp(B)_i$$

Top Transition Point to Middle Transition Point1

a) Generate two sets of random numbers from 0 to 1 equal to the distance of between $LTR_{Middle1}$ and LTR_{Top}. Rnd#1 refers to first set of random numbers and Rnd#2 refers to second set of random numbers.

b) Arrange both sets in descending order with an assigned index number ($i = LTR_{top}$ to $LTR_{Middle1}$) for each random number

c) Calculate the composition using the formula

$$Comp(B)_i = Rnd\#1_i \times \left[\frac{TE_{BH1} - EM1}{D}\right] + Rnd\#2_i \times \left[\frac{EM1 - TempE1}{D}\right]$$

$$Comp(A)_i = 1 - Comp(B)_i$$

First Middle Transition Point to Second Middle Transition Point

$$Comp(B) = 0$$

$$Comp(A) = 1$$

Second Middle Transition Point to Bottom Transition Point

a) Generate two sets of random numbers from 0 to 1 equal to the distance of between LTR_{Bottom} and $LTR_{Middle2}$. Rnd#1 refers to first set of random numbers and Rnd#2 refers to second set of random numbers.

b) Arrange Rnd#1 in ascending order with an assigned index number (i = 1 to (LTR $_{Bottom}$ – LTR$_{Middle2}$) for each random number) and Rnd#2 in ascending order with an assigned index number (i = 1 to (LTR $_{Bottom}$ – LTR$_{Middle2}$) for each random number)

c) Calculate the composition using the formula

$$Comp(B)_i = Rnd\#1_i \times \left[\frac{TempE2 - EM2}{D}\right] + Rnd\#2_i \times \left[\frac{EM2 - EE_{BH2}}{D}\right]$$

$$Comp(A)_i = 1 - Comp(B)_i$$

Bottom Transition Point to BH2

a) Generate one set of random numbers from 0 to 1 equal to the distance of between LTR$_{Bottom}$ and BH2.

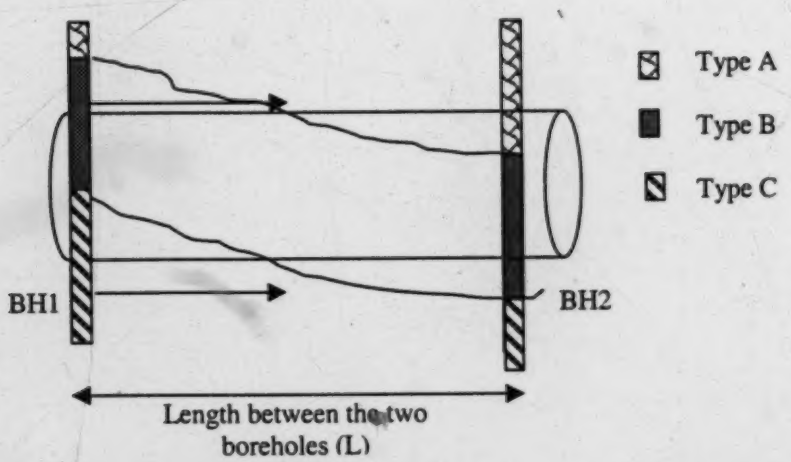
b) Arrange them in ascending order with an assigned index number (i = 1 to (LTR $_{Bottom2}$ – BH2) for each random number). Rnd# refers to the random numbers

c) Calculate the composition using the formula

$$Comp(B)_i = Rnd\#_i \times \left[\frac{SE_{BH2}(B) - TempE2}{D}\right] + \left[\frac{TempE2 - EE_{BH2}}{D}\right]$$

$$Comp(A)_i = 1 - Comp(B)_i$$

THREE SOILS - TRANSITION OF SOILS BOTH AT TOP AND BOTTOM ELEVATIONS WITH (FIGURE 6-13)



This scenario involves one transition point at the top elevation and the other one at the bottom elevation. At the top elevation, transition is from Soil B to Soil A. At the bottom elevation, the transition is from Soil C to Soil B. The following are the steps of the calculating the transition points, and composition of soils. All the transitional probabilities are modified to suit the transitions as explained in Section 6.3.4.

Calculation of Transition Points

a) Generate random numbers between 0 and 1 equal to the length between the two boreholes (Random numbers L times)

b) Arrange the random numbers in a descending order with an assigned index number for each random number

c) Use the following algorithm to determine whether the random number belongs to soil A or soil B.

Random Number <= Modified P_{Top}*(B/A)* ⟶ *Soil A*

Random Number > Modified P_{Top} *(B/A)* ⟶ *Soil B*

d) Identify the index number, which change from Soil B to A. The index number is the top transition length (LTR_{top}) from Borehole BH1.

e) Re-generate random numbers between 0 and 1 equal to the equal to the length between the two boreholes (Random numbers L times).

f) Arrange the random numbers in a descending order with an assigned index number for each random number.

g) Use the same algorithm to determine whether the random number belongs to soil B or soil C to find out the transition point at the bottom elevation.

Random Number <= Modified P_{Bottom}*(C/B)* ⟶ *Soil B*

Random Number > Modified P_{Bottom} *(C/B)* ⟶ *Soil C*

h) Identify the index number, which change from Soil C to B. The index number is the bottom transition point1 (LTR_{Bottom}) from Borehole BH1.

Calculation of the Composition of Soil and the profile of the Transition Curve

Soil section between the two boreholes is divided into three segments to calculate the composition of soils; BH1 to top transition point (or BH1 to bottom transition point), top transition point (or bottom transition point) to bottom transition point (or top transition point), bottom transition point (or top transition point) to BH2. The following abbreviations are used to define the algorithms.

i. End Elevation of Soil B at BH1 = EE_{BH1} (B)

ii. Start Elevation of Soil B at BH2 = SE_{BH2} (B)

iii. Top Elevation of BH1 = TE_{BH1}

iv. Bottom Elevation of BH1 = EE_{BH1}

v. Top Elevation of BH2 = TE_{BH2}

vi. Bottom Elevation of BH2 = EE_{BH2}

vii. Top Transition Distance from BH1 = LTR_{Top}

viii. Bottom Transition Distance from BH1 = LTR_{Bottom}

ix. Composition of Soil A at Point $_i$ = Comp(A) $_i$

x. Composition of Soil B at Point i = Comp(B) $_i$

xi. Random Number at Point i = Rnd# $_I$

xii. Depth of the Tunnel = D

If the top transition point is less than the bottom transition point, two temporary elevations for the curve of Soil B is required (TempE1 and TempE2).

$$TempE1 = EE_{BH1}(B) - \left[\frac{LTR_{Top}}{LTR_{Bottom}} \times \left(EE_{BH1}(B) - EE_{BH1}\right)\right]$$

$$TempE2 = TE_{BH2} - \left[\frac{LTR_{Bottom} - LTR_{Top}}{L - LTR_{Top}} \times \left(TE_{BH2} - SE_{BH2}(B)\right)\right]$$

If the Top Transition Point < First Bottom Transition Point

BH1 to Top Transition Point

a) Generate random numbers from 0 to 1 equal to the distance of LTR_{Top}

b) Arrange them in a ascending order with an assigned index number (i = 1 to LTR_{top} for each random number)

c) Calculate the composition using the formula

$$Comp(B)_i = Rnd\#_i \times \left[\frac{EE_{BH1}(B) - TempE1}{D}\right] + \left[\frac{TE_{BH1} - EE_{BH1}(B)}{D}\right]$$

$$Comp(C)_i = 1 - Comp(B)_i$$

$$Comp(A)_i = 0$$

Top Transition Point to Bottom Transition Point

a) Generate two sets of random numbers from 0 to 1 equal to the distance of between LTR_{Bottom} and LTR_{Top}. Rnd#1 refers to first set of random numbers and Rnd#2 refers to second set of random numbers.

b) Arrange Rnd#1 in descending order with an assigned index number (i = 1 to ($LTR_{Bottom1} - LTR_{top}$) for each random number) and Rnd#2 in ascending order with an assigned index number (i = 1 to ($LTR_{Bottom1} - LTR_{top}$) for each random number)

c) Calculate the composition using the formula

$$Comp(B)_i = Rnd\#1_i \times \left[\frac{TE_{BH1} - TempE2}{D}\right] + Rnd\#2_i \times \left[\frac{TempE1 - EE_{BH2}}{D}\right] + \left[\frac{TempE2 - TempE1}{D}\right]$$

$$Comp(A)_i = (1 - Rnd\#1_i) \times \left[\frac{TE_{BH1} - TempE2}{D}\right]$$

$$Comp(C)_i = (1 - Rnd\#2_i) \times \left[\frac{TempE2 - EE_{BH2}}{D} \right]$$

Bottom Transition Point to BH2

a) Generate one set of random numbers from 0 to 1 equal to the distance of between $LTR_{Bottom1}$ and BH2. Arrange them in descending order with an assigned index number (i = 1 to (L - LTR_{Bottom}) for each random number). Rnd# refers to the random numbers.

b) Calculate the composition using the formula

$$Comp(B)_i = Rnd\#_i \times \left[\frac{TempE2 - SE_{BH2}(B)}{D} \right] + \left[\frac{SE_{BH2}(B) - EE_{BH2}}{D} \right]$$

$$Comp(A)_i = (1 - Comp(B)_i)$$

$$Comp(c)_i = 0$$

If the Top Transition Point > Bottom Transition Point

Between BH1 and Bottom Transition Point

a) Generate random numbers from 0 to 1 equal to the distance of LTR_{bottom}

b) Arrange them in a ascending order with an assigned index number (i = 1 to LTR_{bottom} for each random number)

c) Calculate the composition using the formula

$$Comp(B)_i = Rnd\#_i \times \left[\frac{EE_{BH1}(B) - EE_{BH1}}{D} \right] + \left[\frac{TE_{BH1} - EE_{BH1}(B)}{D} \right]$$

$$Comp(C)_i = 1 - Comp(B)_i$$

$$Comp(A)_i = 0$$

Bottom Transition Point to Top Transition Point

$$Comp(B) = 1$$

$$Comp(A) = 0$$

$$Comp(C) = 0$$

Top Transition Point to BH2

a) Generate one set of random numbers from 0 to 1 equal to the distance of between BH2 and LTR_{Top}.

b) Arrange them in descending order with an assigned index number (i = 1 to (L – LTR_{top}) for each random number). Rnd# refers to the random numbers

c) Calculate the composition using the formula

$$Comp(B)_i = Rnd\#_i \times \left[\frac{TE_{BH2} - SE_{BH2}(B)}{D}\right] + \left[\frac{SE_{BH2}(B) - EE_{BH2}}{D}\right]$$

$$Comp(A)_i = 1 - Comp(B)_i$$

$$Comp(C)_i = 0$$